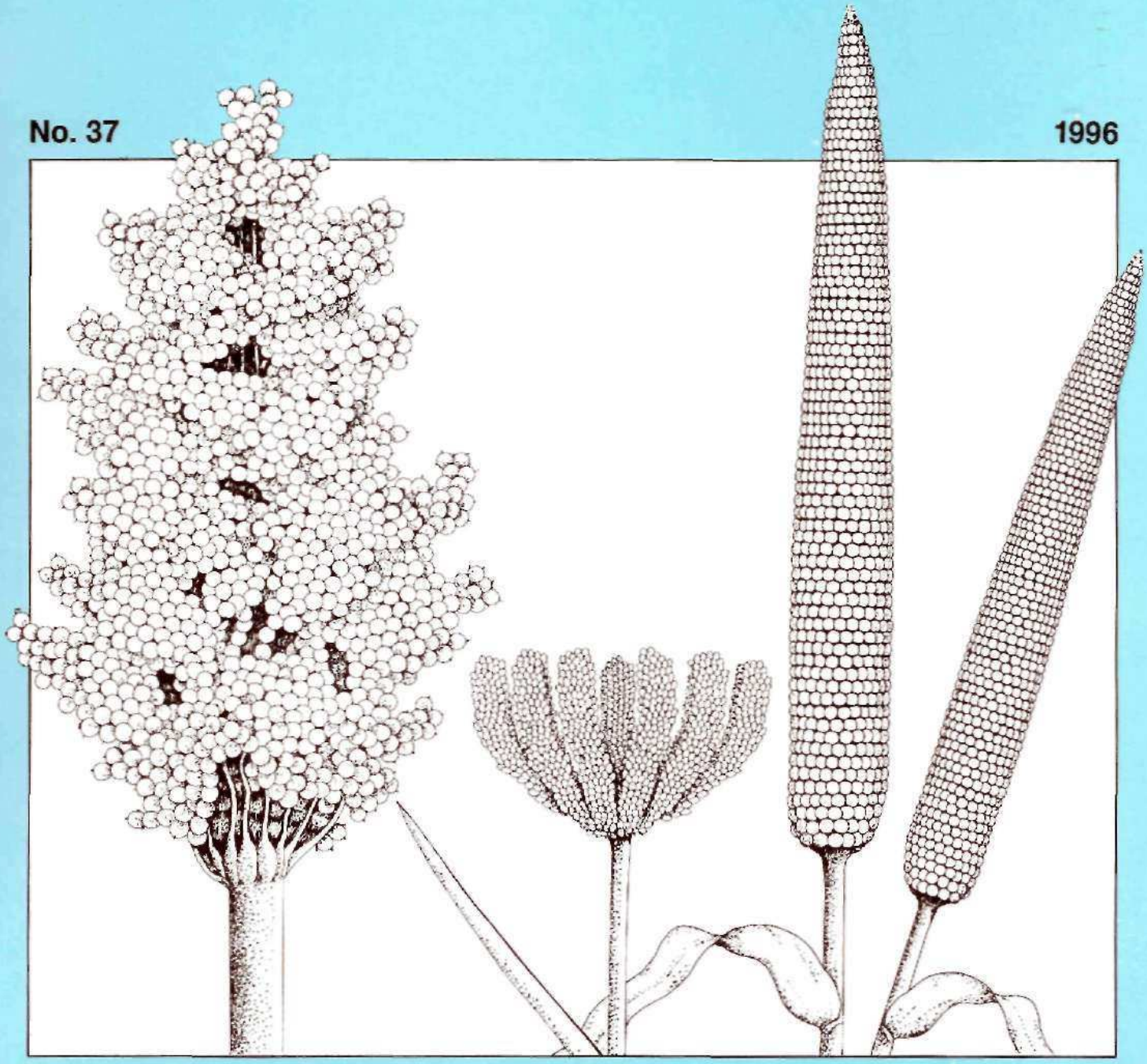
SICNA

International Sorghum and Millets Newsletter

No. 37

1996



International Sorghum and Millets Newsletter

Co-publishers

SICNA
Sorghum Improvement Conference
of North America

ICRISAT
International Crops Research Institute
for the Semi-Arid Tropics

About SICNA

In 1947, sorghum breeders formed an informal working group to meet and review items of interest in sorghum breeding and genetics. This organization was named 'Sorghum Research Committee'. In the 1960s, with the advent of a number of severe disease and insect problems, special half-day sessions, particularly on diseases, became a part of the Sorghum Research Committee. In 1973, a concept was put forward mat all sorghum workers, irrespective of discipline and employer, should meet twice a year to discuss mutual concerns with sorghum research and development. The Sorghum Improvement Conference of North America was that new organization. It is composed of eight disciplinary committees, dealing with genetics and breeding, pathology, entomology, chemistry and nutrition, physiology and agronomy, biotechnology, utilization and marketing, and agribusiness and commercial. SICNA meets formally once a year in conjuction with the National Grain Sorghum Producers Board. A general program of research, education, and developmental activities is prepared by the disciplinary committees. Funding is through membership participation and contributions from commercial donors. Essentially, SICNA represents the United States sorghum activities but accepts reports and encourages memberships from sorghum and millet researchers worldwide.

About ICRISAT

The semi-arid tropics (SAT) encompasses parts of 48 developing countries including most of India, parts of southeast Asia, a swathe across sub-Saharan Africa, much of southern and eastern Africa, and parts of Latin America. Many of these countries are among the poorest in the world. Approximately one-sixth of the world's population lives in the SAT, which is typified by unpredictable weather, limited and erratic rainfall, and nutrient-poor soils.

ICRISAT's mandate crops are sorghum, pearl millet, finger millet, chickpea, pigeonpea, and groundnut; these six crops are vital to life for the ever-increasing populations of the semi-arid tropics. ICRISAT's mission is to conduct research which can lead to enhanced sustainable production of these crops and to improved management of the limited natural resources of the SAT. ICRISAT communicates information on technologies as they are developed through workshops, networks, training, library services, and publishing.

ICRISAT was established in 1972. It is one of 16 nonprofit, research and training centers funded through the Consultative Group on International Agricultural Research (CGIAR). The CGIAR is an informal association of approximately 50 public and private sector donors; it is co-sponsored by the Food and Agriculture Organization of the United Nations (FAO), the World Bank, the United Nations Development Programme (UNDP), and the United Nations Environment Programme (UNEP).

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Ergot - a Global Threat to Sorghum

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Introduction

Productivity of sorghum has increased significantly since the early 1970s in Asia. In 1970, the average sorghum yield in Asia was 747 kg ha^{-1}; ithad increased to 1214 kg ha^{-1} by 1994 (FAO 1996). One of the significant contributors to the increase in productivity was the cultivation of highly productive F_1 hybrid seeds by Indian farmers. In Africa, South America, and Latin America commercial sorghum hybrids are increasingly being used. Farmers in USA and Australia achieve substantial yields from sorghum, and they rely almost totally on hybrid seeds.

Ergot is a serious disease of sorghum that affects the production of F_1 hybrid seeds particularly in male-sterile lines if seed set is delayed due to the lack of viable pollen caused by nonsynchronous flowering of male steriles and restorers. In western Maharashtra and Vidarbha, India, 10-80% losses due to the disease have been reported in seed production plots (C S Sangitrao, personal communication). Similar yield loss is not uncommon in southern Africa. Ergot can also cause widespread damage to male-fertile cultivars in farmers' fields when favourable environmental conditions occur at flowering. In 1986, an epidemic on a newly introduced hybrid, CSH 11, caused serious losses in Karnataka, India. As a result, the otherwise productive hybrid was withdrawn from cultivation (R Bandyopadhyay, unpublished). Ergot is a disease of the ovary; it reduces grain yield because infected flowers do not produce grains. The disease lowers grain/seed yield and quality, makes threshing difficult, reduces germination and seedling emergence, and predisposes seedlings to other diseases (McLaren 1993). Until 1995, the disease was limited to Asia and Africa in distribution.

The sorghum industry around the world was shocked by the sudden observation and rapid spread of ergot in Latin America beginning in Brazil in 1995. A similar epidemic broke out in Australia in April 1996. The global appearance of ergot has made US sorghum workers and quarantine officials feel rather vulnerable to the potential introduction of ergot. That vulnerability was underscored with news that ergot-contaminated seed from Brazil may have been shipped to other South American countries and to the Bajio of Mexico. If established in Mexico, US scientists wondered how quickly it might spread across the border into South Texas where the pathogen would have direct access to the Great Plains states in central USA where most of the country's sorghum is grown.

The purpose of this review is to provide a current status report on sorghum ergot for the benefit of those who are interested to learn more about the disease. A bibliography of the disease replaces the usual Selected References section in this issue of ISMN.

Widening geographical influence

Sorghum ergot was first observed in India in 1915 and was described by M^{c}Rae in 1917. That it was more widespread in India was confirmed in 1948, when Ramakrishnan recorded ergot in Andhra Pradesh State. In 1927, ergot was sampled in Burma (IMI accession 14172). All reports and samples represent the pathogen *Claviceps sorghi.* In 1991, ergot was also reported from Taiwan (Chen et al. 1991).

In Africa, sorghum ergot was recognized first in the eastern region, having been sampled in Kenya in 1924 (IMI accession 93464), Uganda in 1926 (IMI accession 14170), and Tanzania in 1949 (Wallace and Wallace 1949). In 1953, ergot was reported in South Africa (Doidge et al. 1953), in 1955 in Nigeria (IMI accession 62801), Zambia in 1965 (Angus 1965), Botswana in 1974 (Molefe 1975), Ethiopia in 1976 (IMI accession 225570), and Mozambique in 1984 (Plumb-Dhindsa and Mondjane 1984). In 1986, ergot was confirmed in Zimbabwe, Swaziland, and other southern African countries (de Milliano et al. 1991). All reports and samples from Africa represent the distinctive pathogen *Claviceps africana* (Frederickson et al. 1991).

The worldwide distribution of *C. africana* is currently expanding rapidly. In 1991, the ergot pathogen in Thailand was, contrary to expectations, identified as *C. africana,* not C. *sorghi* (Frederickson et al. 1991), and in Japan, one of the ergot species parasitizing sorghum was similarly identified (Mantle and Hassan 1994). The same

pathogen caused a widespread ergot epidemic in Brazil in 1995 (Reis et al. 1996) and is possibly now in Argentina, Bolivia, Colombia, and Paraguay. This year extensive *C. africana* infections have been confirmed throughout Queensland, Australia. Ergot presents a very serious threat to sorghum production in Central and North America, although it has yet to be recorded in USA.

Quarantine and the seed trade

The sources of recent *C. africana* infections in Thailand and Japan, and the Americas and Australia in particular, have not been determined, although seed traded intercontinentally for commercial or research purposes is obviously implied. Once arrived in a country, however, the disease most probably relies on airborne dispersal, that is likely to be a more important means of dissemination between adjacent countries or states on the same continent. Therefore, quarantine must play the leading role in continued exclusion of the pathogen. The initial source of *C. africana* inoculum is unclear even in Africa; sclerotia, sphacelia, and honeydew are all likely possibilities. Although *C. africana* sclerotia germinate with difficulty (Frederickson et al. 1991, Bandyopadhyay 1992), only a small source of inoculum is needed under favorable conditions to initiate an epiphytotic in male-sterile sorghum (Frederickson et al. 1989 and 1993). Imported seed must therefore be viewed as an important source of infection and thoroughly inspected for sclerotia, sphacelia, and honeydew before distribution is permitted. For continued exclusion of the disease, e.g., from the USA, seeds with the slightest contamination must be rejected.

Reports of ergot in Latin America and the probable quarantine and other trade restrictions instituted to prevent or slow the spread of ergot to other Western Hemisphere countries including USA will have an immediate, negative impact on the US sorghum industry. The global nature of the US sorghum industry ensures that ergot in such other countries as Brazil and Argentina will have an immediate economic effect; there will be a loss or limitation of winter nursery facilities and sorghum markets in Latin America, due to the banning of seed imports from ergot-affected countries into non-ergot countries. With every additional Western Hemisphere country affected by ergot there is both an increased negative impact on the US sorghum industry, and an increased potential for ergot introduction into USA, either through contaminated seed, or through natural spread across the southern border with Mexico. There will be similar effects in such other countries where ergot has not yet been observed.

If established in USA, ergot could have two especially devastating effects on the sorghum industry; through direct damage to hybrid seed production fields, and through the loss of international and domestic markets. Most hybrid seed production in USA is done in the high plains of the panhandle region of Texas where vast areas of highly vulnerable male-sterile sorghums could be heavily damaged, and provide for rapid spread of the disease. The hybrid seed produced in ergot-infested fields would not only be of lower quality, but there would be less of it; it would require additional sanitation procedures, and it would be restricted in both US and international commerce. The presence of ergot in USA may also cause the loss of some international markets for sorghum, even where production may be from fields or areas of USA not yet affected by ergot.

Toxicity to animals

One of the key issues of ergot on cereals is the stigma associated with the toxicity of alkaloids produced in sclerotia. Mantle (1968a) and Mantle and Waight (1968) first reported that *C. africana* sclerotia contain unique clavine alkaloids, chiefly dihydroergosine. These researchers, together with Mower (1973), Frederickson (1990), and Frederickson et al. (1991) have found that sclerotial alkaloid content varies between 0.02 and 0.98% w/w, 88% of which is dihydroergosine. Other clavine alkaloid intermediates in the biosynthetic pathway to dihydroergosine were confirmed by TLC, HPLC, and mass spectrum analyses as pyroclavine, festuclavine, chanoclavine, and dihydroelymoclavine (Mantle 1968, Frederickson 1990, Frederickson et al. 1991, Mantle and Hassan 1994, Reis et al. 1996). Ramakrishnan (1948) and Mantle (1968a) noted the total absence of alkaloids in sclerotia of *C. sorghi,* the Asian pathogen. The account by Chinnadurai and Govindaswamy (1971a) of 0,025 and 0.08% w/w alkaloid in *C. sorghi* sclerotia is probably erroneous, since they did not specifically extract and assay alkaloid, but assayed powdered sclerotia. The result probably reflects the general detection of indolic compounds by the reagent p-dimethylaminobenzaldehyde. Analysis for dihydroergosine and the other minor alkaloids in sclerotia can thus distinguish between *C. africana* and *C. sorghi,* The question of the potential toxicity of sorghum ergot sclerotia inevitably arises through analogy with *C. purpurea* and *C. fusiformis,* that synthesize such potent alkaloids as ergotamine and agroclavine (Youngken 1947, Shone et al. 1959, Loveless 1967). In contrast to the agalactia exerted by agroclavine on pregnant and lactating mice and sows (Shone et al. 1959, Mantle 1968b, Mantle 1969), diets of up to 50% sclerotia of *C. africana* (15 mg alkaloid day^{-1}) following insemination or before parturition, had no effect on blastocyst implantation, litter size, pup growth, or

lactation in mice (Mantle 1968a and b, 1969 and 1990). Therefore it is highly unlikely that sclerotia-contaminated sorghum grain has any implications for animal health.

Phadnik et al. (1994) reported that sorghum ergot sclerotia contained clavine derivatives and the total alkaloid content varied from 0.008 to 0.032% (expressed in terms of ergometrine base). The low alkaloid content explains the high LD_{50} value (1.875 g kg^{-1}) of sorghum ergot in experimental mice, compared to 100 mg kg^{-1} in rhesus monkey for pearl millet ergot. Mortality in mice occurred even at a single oral dose of 0.75 g kg^{-1} body weight. Common symptoms of toxicity were diarrhoea, dyspnea, muscular spasm, hyperexcitability, and gangrene. In chronic toxicity studies, diarrhoea was observed on the second day after administering one-sixth of the LD_{50}. Significant reduction was observed in body weight and relative organ weight of lungs, liver, heart, spleen, and kidney. Shrinkage at the tail tip, gangrene, and sloughing of tail also occurred. Histopathological changes in the affected part of the tail include occlusion of the blood vessels due to the presence of red thrombi and necrosis. Further critical studies on toxicity to livestock are required to determine if ergot sclerotia are hazardous to animals.

There are indications that sclerotia of *Claviceps* species found in Japan contain the alkaloid palielavine (T Tsukiboshi, personal communication). There is no information on its potential toxicity.

Symptoms

Ergot only attacks unfertilized ovaries. Few or all flowers in an inflorescence may be infected. The most obvious external sign of the disease is the exudation, from the infected flowers, of honeydew, a thin-to-viscous, sweet, sticky fluid that gives the name 'sugary' or 'honeydew' disease to the malady.

The ovary is infected much before the initiation of honeydew exudation. In fact, the earliest symptoms of infection can be seen on the ovary if flowers are dissected 3-4 days after infection. The infected ovary appears dull green and smaller (*C. sorghi*) or larger (*C. africana*) than the healthy, fertilized ovary which is dark green and round. Superficial, white mycelial growth initially appears at the basal end of the ovary and extends upward as the pathogen colonizes ovary tissues both internally and externally. Finally, the complete ovary is converted into a white, fungal mass, or sphacelium, that is visible between the glumes. Then, honeydew exudation begins.

Newly formed honeydew droplets are colorless and transparent, and become progressively opaque. Honeydew can be uniformly yellow-brown to pink, or superficially matt white. Continued production of honeydew causes droplets to lengthen, smearing seeds and leaves, and falling to the ground. When infection is severe, affected panicles can be recognized from a distance. They may be white with fresh honeydew, or black if the honeydew is saprophytically colonized.

During wet or humid periods at relative humidities above 90%, the ergot fungus produces secondary conidia on the surface of the honeydew which appear as a white scum or powdery growth. This white growth on the honeydew appears wherever it is present including the panicle, leaves, and soil. If moist conditions persist, infected flowers may be highlighted by several saprophytes (one of these is *Cerebella* sp) that grow on the honeydew as a large, black, globose convoluted mass concealing the sphacelium. If conditions are warm and dry after the honeydew is formed, it desiccates, forming a brittle, hard, white crust on panicles and leaf surfaces. Under warm dry conditions, sphacelia gradually harden to form solid dense sclerotia. But, in moist conditions, the sphacelia shrivel and become fibrous, and fail to develop into sclerotia.

Ergot is not the only cause of honeydew exudation in sorghum. Insects, such as aphids, also secrete sticky honeydew that is often interspersed with the white molts of the insects. Leaves can also exude honeydew at temperatures below 20°C due to a physiological disorder called 'leaf sugary disease'. Honeydew from insects and leaf sugary disease does not contain spores of the ergot fungus.

Claviceps africana

According to Frederickson (1990) and Frederickson et al. (1991), when ovarian tissues have been fully colonized after 6-8 days, individual infections of *C. africana* become visible as bulky, soft, white, oval to spherical fungal sphacelia, protruding between the glumes. Honeydew exudation commences a day later, as a small drop of transparent liquid devoid of conidia at the tip of the sphacelium. Over successive days, the honeydew droplet enlarges, appearing superficially matt white, but non-viscous, and transparent below. The surface layer contains germinating macroconidia with aerially supported secondary conidia (Frederickson et al. 1989). Honeydew droplets may spill in a cascade over panicles rendering them maeroscopically white in appearance, a very distinctive symptom. Following rain, small patches of white honeydew may collect on the ground at the base of an infected plant. Under dry conditions, honeydew from infected florets forms viscous, orange-brown droplets. After several weeks, the soft, sphacelial tissues are replaced

by hard, compact, sclerotia, 4-6 x 2-3 mm, still largely enclosed by the glumes. A small sphacelial cap remains infected. Dried honeydew may encrust panicles.

Claviceps sorghi

Frederickson and Mantle (1988) and Frederickson (1990) reported that honeydew is the first sign of infection, visible after about 8-10 days. However Bandyopadhyay et al. (1990) noted a visible stroma after 5-6 days, concurrent with transparent honeydew. Honeydew superficially white due to secondary conidiation can occur when relative humidity is high (90%), but honeydew is more usually brown and viscous or pink to light honey in color under field conditions in India (Kulkarni et al. 1976, Mughogho 1986) because normally humidity remains low (<80%) when honeydew exudation occurs in nature. The sphacelia are cylindrical, curved or straight, bilaterally-grooved, visible 1-2 days after honeydew exudation begins (Frederickson et al. 1991). At maturity, the protruding sphacelial portion of the parasitic biomass is discolored, whilst the proximal part, largely within the glumes, contains the true sclerotium, composed of compact, white plectenchymatous tissue under a thin, red-brown cortex (Sangitrao and Bade 1979b; Frederickson et al. 1991). The shape and size of mature sclerotia depend on host genotype, environment, and nutritional factors (Fig. 1). They measure 3-14 x 1-2.5 mm (Frederickson et al. 1991), 9-20 x 1.5-2 mm, and 4-7 x 1.5-2 mm (Kulkarni et al. 1976), 10-25 x 4-6 mm (Ramakrishnan 1948).

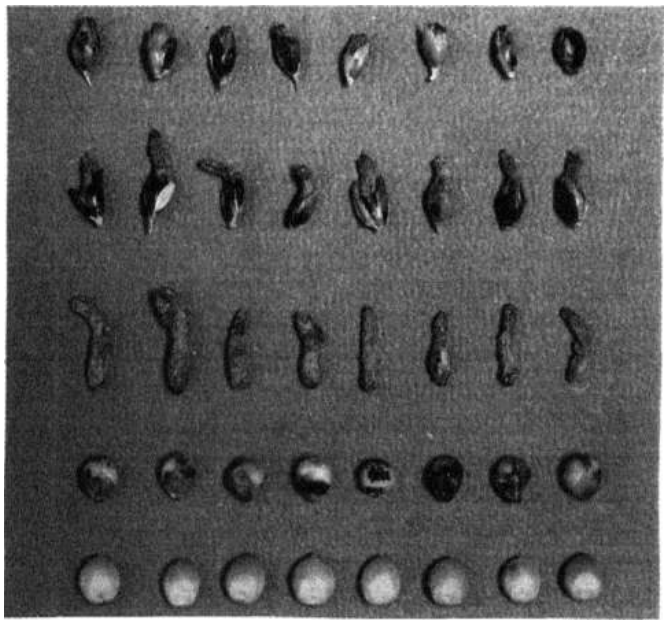

Figure 1. Differences in the size of *Claviceps sorghi* sclerotia, and grain discoloration because of honeydew. Top to bottom: small sclerotia concealed inside glumes; long sclerotia with glumes; long sclerotia removed from the glumes; discolored seed; healthy seed. Sclerotia were collected from the same field in Akola, Maharashtra State, India.

Claviceps species

Tsukiboshi and Frederickson (unpublished) describe sphacelia as elongate structures, straight or curved, the protruding part conical in shape. Sclerotia are purple-black, 14 x 2 mm, capped by a very small sphacelial remnant. Orange-yellow honeydew is exuded from infected florets, upon which secondary conidiation never occurs.

Causal organisms

Current evidence suggests that sorghum is uniquely host to three different ergot pathogens: *Claviceps sorghi* (Kulkarni et al. 1976), *Claviceps africana* (Frederickson et al. 1991) and a *Claviceps* species (possibly *C. panicoidea). Claviceps sorghi* is found only in Asia, whereas C. *africana,* the typical sorghum pathogen of Africa (Frederickson 1990, Frederickson et al. 1989 and 1991), is also known in Thailand and Japan (Frederickson et al. 1991, Mantle and Hassan 1994), and most recently in Brazil (Reis et al. 1996) and Australia (M Ryley, personal communication). The third pathogen, *Claviceps* species, appears to be present currently only in Japan (T Tsukiboshi, personal communication). The anamorphs of *C. africana* and *C. sorghi* are both known as *Sphacelia sorghi* M^{c}Rae, *Claviceps africana* and C. *sorghi* have been compared and contrasted in a number of features, including phytopathology, teleomorphs, alkaloids, and honeydew sugar composition by Frederickson et al. (1991).

Anamorph of *C. africana* (S. *sorghi*)

Frederickson et al. (1991) describe the sphacelial stage as a highly convoluted, white parasitic body (5-8 mm long) bearing in discrete pockets the hyaline, mononucleate, oblong to oval macroconidia of 9-17 x 5-8 µm, slightly constricted at the center and with 2 polar vacuoles, and spherical microconidia 2-3 µm in diameter. Pear-shaped secondary conidia borne on sterigma-like processes are 8-14 x 4-6.5 µm with a distinct, protruding hilum.

Anamorph of C. *sorghi* (*S. sorghi*)

Bandyopadhyay et al. (1990) describe hyaline, unicellular, elliptic to oblong macroconidia with round ends of

13.2 x 7.3 µm. Pyriform, hyaline, secondary conidia are 12.1 x 7.2 µm. Hyaline, round to obovate microconidia are 3 x 4 µm. The original description of Kulkarni et al. (1976) describes macroconidia of 12-19 x 5.8 µm, whereas Frederickson et al. (1991) give measurements as 8-19 x 4-6 µm.

Anamorph of *Claviceps* species

Conidia are small, 5-11.3 x 2.5-5 µm; no secondary conidia are produced (personal observation, Frederickson and Tsukiboshi).

Teleomorph of *C. africana*

Frederickson (1990) and Frederickson et al. (1991) describe the stromatal origins as pale, globose proliferations of the sclerotium. Fully-extended stipes (8-15 x 0.3-0.6 mm) are pigmented purple, adjacent to the capitulum. Capitula (0.5-1.3 mm) are sub-globose, and intensely purple. Perithecia are 86-135 x 123-226 µm; mature asci in situ, 140 x 3.2-4.2 µm; 8 ascospores of up to 45 x 0.8-1.2 µm. Mower et al. (1973) depicted, but did not describe, stromata of *C. africana* from Nigeria.

Teleomorph of *C. sorghi*

Kulkarni et al. (1976) gave an incomplete description of the teleomorphic stage: 2-3 stromata, stipe, and capitula of unspecified sizes. Perithecia, 132.8-232.4 x 66.4-124.5 mm. Asci (56-112 x 2.4-3.2 µm), cylindrical with tapering ends and a hyaline apical cap; 8 ascospores, filiform, 40-85 x 0.4-0.8 µm. The description of the teleomorphic stage provided by Sangitrao (1982) is almost similar to that of Kulkarni et al. (1976) except for a few minor details. Frederickson et al. (1991) describe the stipes as 6-8 x 0.5 mm, burnished-bronze/ deep terracotta in color. Capitula 0.7 mm diameter, buff-colored but with darker, papillate perithecial ostioles, the stipe insertion point is surrounded by a white frill. Perithecia measure 130-250 x 60-125 µm. The white frills were not described by Kulkarni et al. (1976) and Sangitrao (1982).

Teleomorph of *Claviceps* species

According to Tsukiboshi (personal communication) the stromata resemble those of *C. sorghi,* with a buff to terracotta stipe and terracotta-colored capitulum, but lacking a frill at the capitulum base. Ascospores are 92.5-205 µm long, and larger than those of *C. sorghi*.

Biology of the pathogens

Path of infection

The path of infection by *C. africana* (Frederickson 1990) and *C. sorghi* (Frederickson and Mantle 1988) have been studied in great detail. The latter study has been corroborated by ICRISAT (1989) and Bandyopadhyay (1992).

Ergot is a tissue-specific disease; only pistils are infected. The patterns and events during the course of infection for *C. africana* and *C. sorghi* are similar. The stigma is the principal site of infection, although conidia can germinate (Frederickson 1990) and infect (R Bandyopadhyay, unpublished) through the style and ovary wall. The primary route of ovary colonization is as follows. Conidia germinate on the stigma producing 1-4 germ tubes. After penetrating the stigmatic papillae, the infection hyphae grow intercellularly through the stigmatic rachis, progress through the transmitting cells of the style up to the ovary, then down through the ovary in the inner ovary wall tissues adjacent to the ovule, and finally reach the vascular bundles within the rachilla. Only upon contact with these vascular bundles docs the fungus rapidly colonize the ovary acropetally. Bundles of hyphal strands grow intercellularly along the inner layer of the ovary wall, integuments, and epidermis. The fungus also colonizes the ovary tissues from the focus of the initial infection tract. Ovule tissues are colonized by the invasive hyphae from the ovary. Finally, the fungus replaces the ovary with its own deeply involuted soft mass, called sphacelia. Initially, sphacelia secrete a clear liquid which becomes more opaque (honeydew) upon production and release of macroconidia originating from short conidiophores on the surface of sphacelia. The sphacelia possess several internal locules. Conidiophores lining the locule also produce macroconidia that stay trapped within the locule. The sphacelia later harden and are converted into sclerotia. Throughout the course of invasion, the fungus retains contact with the vascular bundles in the rachilla without destroying it, and thus allows continued nutrient transport to support the sphacelia and honeydew production.

Time course of infection and colonization events

A summary comparison of time-course of infection events from reports by Sangitrao (1982), Frederickson and Mantle (1988), ICRISAT (1989), Frederickson (1990), and Bandyopadhyay (1992) is given in Table 1. The first two reports deal with isolates of *C. sorghi* collected from the same location (Akola, India), but differ in environmental conditions used during the experiments.

Table 1. Colonization of different parts of the sorghum ovary by *Claviceps africana* and C. *sorghi* on a time scale.

Event	*Claviceps africana*[1]	*Claviceps sorghi* Report A[2]	Report B[3]	Report C[4]
Germination of conidia	15-24 h	16 h	12 h	12 h
Infection hyphae at the stylar end of ovary	-	3 d	2 d	2-3 d
Infection hyphae at the basal end of ovary	4 d	5 d	3 d	5 d
Complete ovary colonized	6-8 d	8-10 d	5-8 d	6-7 d

Source: 1. Frederickson (1990). Study conducted at 10-30°C, and 65-100% RH; 2. Frederickson and Mantle (1988). Study conducted at 10-30°C, and 65-100% RH; 3. ICRISAT (1989). Study conducted at 14-28°C, and 45-90% RH; and 4. Sangitrao (1982). Study conducted at 17-33°C, and 30-60% RH.

In the study by Frederickson (1990) on *C. africana,* conidia germinated on stigmas within 15-24 h, and the ovary wall had been substantially colonized, with hyphae visible even in the peripheral ovule tissues, at the base of the ovary and on the lower ovary surface, by day 4. At 6-8 days the macroscopic sphacelium was visible.

The study by Frederickson and Mantle (1988) on *C. sorghi* occurs within the constraints of diurnal temperature and relative humidity (RH) oscillations of 10-30°C and 65-100% RH and can be compared directly to the study of *C. africana* (Frederickson 1990), which occurred concurrently, Macroconidia germinated on stigmas within 16 h of deposition. Hyphae travelled to the top of the ovary in 3 days. Predominantly abaxial colonization of the inner ovary wall proceeded, and by day 5, hyphae were visible at the ovary base. At day 6, ovary base colonization was so extensive that hyphae emerged onto the ovary surface, permitting acropetal, surface colonization in the next 2-3 days. Also on day 6, hyphae had penetrated the chalazal region of the ovule. Subsequent colonization was very rapid so that at 8-10 days, the whole ovary had been colonized, sphacelial fructifications were evident, and honeydew exudation commenced.

Influence of environment

In vitro germination of conidia

Claviceps africana. In vitro on potato dextrose agar (PDA) or water agar (WA), macroconidia began to germinate after 12 h at 14-35°C; the optimum temperature was 19°C (Frederickson 1990, McLaren and Wehner 1990), and conidia failed to germinate at 37°C. Germination was always iterative, i.e., producing a secondary conidium. However, the sterigma-like process bearing the secondary conidium became extended with increasing temperatures to a maximum of five times the conidial length at 30°C (Frederickson 1990). The proximity of the macroconidia to pollen stimulated germination by germ tube formation. Macroconidia were unable to germinate once the sucrose content of the media reached 10% w/v.

Claviceps sorghi. Frederickson (1990) observed that macroconidia required 16 h to germinate in vitro at all temperatures. Conidia germinated from 14°C to 37°C, optimally at 35°C. Germination percentage did not vary significantly over the 18-30°C range but was always iterative. At 35°C, germination was in the form of two, sometimes three, germ tubes. Macroconidia were able to germinate even with 34% w/v sucrose in the media.

Germination of macroconidia was studied on water agar with or without amendment with a suspension of stigma macerate at 15, 20, 25, 30, and 35°C (R Bandyopadhyay, unpublished). Macroconidia germinated in two modes, iteratively from lateral sides by producing thin, slender, sporogenous germ tubes terminating in secondary conidia, and noniteratively by producing thick germ tubes from both ends. Macroconidia almost always germinated noniteratively in association with stigma macerate, and iteratively in the absence of stigma macerate. When in contact with stigma macerate agar, 96-100% macroconidia germinated noniteratively at 15-30°C, but only 30% at 35°C after 48 h. Germ tubes were 10 times smaller (40 µm) at 15°C than at 20°C. On water agar, iterative germination was 47% at 15°C, 94% at 20°C, 6% at 25°C, and 3% at 30°C; no germination was observed at 35°C. Iterative germination is responsible for the production of secondary conidia, whereas noniterative germination is a prerequisite for infection. These data suggest that infection can occur within a wide tern-

perature range, but 20±2°C is most favorable for secondary sporulation.

Claviceps species. At the optimum temperature of 27.5°C, conidia of *Claviceps* species begin to germinate in vitro after only 10 h producing four germ tubes. At 20-25°C germination is iterative (T Tsukiboshi, personal communication).

In vivo germination of conidia

Germination of macroconidia of *C. africana* on stigmas to form penetrative germ tubes started 15 h after inoculation (Frederickson 1990) under diurnal temperature oscillations of 12-28°C. Iterative germination of macroconidia was never seen on stigmas. Frederickson and Mantle (1988), noted microconidia of C. *sorghi* germinating by one to several germ tube(s) within 16 h at 12-28°C and Bandyopadhyay et al. (1990) observed the same thing after 24 h at 14-28°C following inoculation onto the stigma.

Sphacelia and sclerotia formation, and sporulation in vivo

Temperature plays a major role in the rate of colonization of ovary tissues by C. *sorghi* (R Bandyopadhyay, unpublished). At constant temperature, sphacelia appeared at the basal end of the ovary 5 days after inoculation (DAI) at 25°C, 6 DAI at 20°C, and 8 DAI at 15°C. Honeydew exudation began 6-7 DAI at 25°C, 7-8 DAI at 20°C, and 13-14 DAI at 15°C. Therefore, the rate of colonization was slower, and more obviously, sporulation was delayed at lower temperatures. However, constant temperatures do not occur in nature. With diurnal variations in temperature, differences in colonization rates were less discrete in growth chamber studies. With day/night temperatures of 35/28°C (RH 90% for 2 h d^{-1}) and 28/23°C (RH 90% for 16 h d^{-1}), sphacelia were visible at the hilar end of the ovary 3 DAI compared with 5 DAI at 24/14°C (relative humidity 90% for 12 h d^{-1}). Honeydew exudation began 5 DAI at 28/23°C, and 6 DAI at 35/28°C and 24/14°C. Production of honeydew and formation of secondary conidia were most profuse at 28/23°C, followed by 24/14°C, and least at 35/28°C (Bandyopadhyay et al. 1990). Conditions favorable for the production of secondary conidia are least conducive for the production of microconidia, and vice-versa. For example, the proportion of microconidia in the honeydew was 17.5% at 35/28°C compared with 4% at 28/23°C.

Sangitrao and Bade (1979a) reported that low temperature and RH increase the incubation period (inoculation to honeydew production). Sclerotial formation was favored by dry weather. Bandyopadhyay et al. (1990) found that temperatures of 14-28°C and RH above 90% for 12-16 h favored conidial, but not sclerotial, production. Higher temperatures of 28-35°C and <80% RH for 12 h were conducive to sclerotial formation (R Bandyopadhyay, unpublished).

Formation of secondary conidia

Increased RH, leading to continued exudation of 'thin' honeydew stimulates iterative germination of macroconidia at the honeydew surface, and results in the formation of secondary conidia in both *C. africana* and C. *sorghi.* Secondary conidiogenesis is unique because of the rapidity and the manner in which it occurs in the honeydew (Frederickson et al. 1989, Bandyopadhyay et al. 1990). Macroconidia inside the 'thick' honeydew do not usually germinate because of the high osmotic potential caused by the high sugar concentration in the honeydew matrix. However, being hygroscopic, the honeydew surface might absorb water from the atmosphere. This would lower its osmotic potential and make the honeydew 'thin'. As a result, under humid conditions, macroconidia on the honeydew surface germinate by two methods. In the first method, macroconidia germinate by long, thick, branched or unbranched germ tubes that enmesh to form a firm hyphal mat which provides a stable surface on the otherwise flowing, inner fluid of the honeydew. The second method of germination is iterative and involves the extension of germ tubes outside the honeydew surface. These germ tubes are functionally conidiophores terminating in apical secondary conidia that are easily detachable and disseminated by wind.

In spore-trapping experiments, a diurnal pattern of secondary conidia concentration was evident, with the greatest occurrence at nightfall, coinciding with the sharp rise in RH and fall in temperature (Frederickson et al. 1989 and 1993). Secondary conidiation did not occur when there were several hot, dry days in succession.

Germination of sclerotia

Claviceps africana

Most attempts by Frederickson (1990) to germinate sclerotia proved futile, with only 5% germination after 16 weeks of incubation in sterile sand at a range of temperatures from 4° to 28°C. However, Frederickson et al. (1991) subsequently reported that 10% of sclerotia from Matopos, Zimbabwe, maintained for 1 year in dry storage at 20-25°C, germinated after 4 weeks of burial 3 cm deep in moist soil, and diurnal temperature oscillations of 10-28°C. Globose, creamy-white initial germination

structures were first seen. By 6 weeks, 80% of the sclerotia had germinated, with differentiating stipes and capitula. Few stromata survived to maturity. Mower et al. (1973) reported stromata of a Nigerian pathogen but did not describe the conditions for inducing germination. Mantle (1968a) incubated sclerotia of a Nigerian pathogen at 24°, 27°, and 30°C, achieving initial germination after 4 weeks at 27°C, which was subsequently aborted.

Claviceps sorghi

In Bangalore, India, Kulkarni et al. (1976) induced germination by incubation of small, hard, sclerotia in soil in petri dishes. Initial germination structures were observed after 35 d in 19 of 24 sclerotia. Full differentiation to stromata was seen after 45 d. Details of environmental conditions were not given. Frederickson et al. (1991) reported germination of elongate sclerotia to give stromata after 5 weeks of incubation on moist sand at 24°C. In Akola, India, Sangitrao (1982) reported stromata differentiated in 50-55 d in up to 55% sclerotia.

Sangitrao (1982) also conducted detailed studies using a sclerotial germination assembly that gave consistent germination of sclerotia at 27°C. Among the different substrates tested, sclerotia germinated best when placed horizontally flat on moist sterilized sand. Sclerotia placed vertically with either end buried did not germinate. Fragments of sclerotia with intact basal ends germinated to produce stroma. Fragments from other parts did not germinate. Sclerotia were viable after storage for 3 years at room temperature in the laboratory. Although field-exposed sclerotia failed to germinate, sclerotia buried up to 60 cm deep in soil in the greenhouse germinated readily in the germination assembly. Sclerotia germinated at 5-50°C, 20-30°C being the optimal range. Host genotypes had significant effects on germination. While 50-55% sclerotia germinated from CK60A and IS 84, germination was about 25-35% for sclerotia obtained from such genotypes as 2077A, CSH 1. and R 473. Fungicides Aureofungin®, Bavistin®, Ceresan®, thiram, and Captan® did not inhibit germination completely, but reduced it to some extent.

Claviceps species

In contrast to C. *africana* and C. *sorghi,* sclerotia of *Claviceps* species germinate very easily on moist sand under scattered light at 25°C. Germination is approximately 50% after 1 month. Germination has also been observed in the field (T Tsukiboshi, personal communication).

Pollen-pathogen-environment interaction

Flowering behavior

Since the ergot pathogens infect and colonize only the gynaecia, knowledge of the inflorescence is essential to understanding the disease. Flowering behavior of sorghum has been described in detail (Stephens and Quinby 1934, Quinby 1958, House 1985). The sorghum panicle is a raceme. Anthesis in spikelets occurs basipetally. During anthesis, the glumes normally open in the morning, the stigma and anthers emerge, anthers shed pollen to pollinate the stigma, and later the glumes close. However, the flowering process is known to vary significantly in different environments and genotypes. For example, in some genotypes stigmas emerge from glumes and remain exposed at least 72 h before anthesis, while in others a cleistogamous condition occurs. The time of flower opening during the day, duration of flower opening, viability of pollen, and the duration and extent of stigma receptivity, all depend on host and environmental conditions. For example, almost all spikelets flower during the night and pollen loses viability after 5 h when sorghum flowers at 26-39°C and 25-60% RH (Stephens and Quinby 1934), but at 10-30°C and 30-95% RH, anthesis occurs only after sunrise, and pollen remains viable for longer periods (Sanchez and Smeltzer 1965). Host factors also determine pollen production, stigma receptivity, stigma size, and other floral characters.

Infection and pollination on a time scale

The spikelet parts most critical for infection and colonization are stigma and anthers. Normally, a stigma is pollinated soon after it is exposed, pollen germinates within 30 min, and fertilization occurs within another 2-12 h (Stephens and Quinby 1934, Artschwager and McGuire 1949). On the other hand, conidia require 8-12 h for germination on the stigma, and 36-48 h to reach the base of the ovary (see Table 1). However, the times for these events vary from floret to floret and are strongly influenced by the environment. For example, fluorescence microscopy studies showed that not all pistils were fertilized even 48 h after pollen shed and successful pollination (R Bandyopadhyay and N W McLaren, unpublished observations).

Relationship between pollination, fertilization, and ergot infection

Several studies have shown that effective pollination and fertilization make pistils escape or resist ergot (Futrell and Webster 1965, Sangitrao 1982, Musabyimana et al. 1995). In an experiment using a fluorescence microscope,

the progress of pollen tube growth and fungal growth was traced at 24-h intervals in pistils of spikelets inoculated 4, 3, 2, and 1 d before or after anthesis, and also at anthesis (Bandyopadhyay et al. 1992). The percentage of spikelets with pollen on the stigma (pollinated), and pollen tubes in ovules (fertilized) were calculated from the microscopy data. The percentage of infected spikelets was calculated from the records of the number of inoculated and infected spikelets in the field. When pollen and conidia were placed concurrently on the stigma, pollen germinated earlier than conidia, and the pollen tube reached the embryo sac faster than the colonizing infection hypha. In pollinated and fertilized pistils, the fungus grew slowly, or failed to grow, thereby reducing ergot severity. In a few cases, infection hyphae and pollen tube grew together up to the ovule, and, as a result, both sphacelia and grain developed together in some spikelets. Data showed that spikelets inoculated 1-4 d after anthesis were all pollinated, but 7.8% were not fertilized and thus remained susceptible, as confirmed by data showing 4-10% ergot severity in the field. Ergot severity increased to 52-95% in spikelets inoculated 1-4 d before anthesis, since the efficiency of fertilization was low. Among these spikelets, 91-100% were pollinated, but only 11-14% were fertilized. Therefore, efficient pollination did not ensure high fertilization rates. The data also show that fertilization was effective in controlling ergot, but that it did not prevent the pathogen from colonizing a few pistils.

Effect of environment on pollination, infection, and their interaction

Futrell and Webster (1965) suggested that any factor that prolongs the period from flower opening until fertilization, promotes ergot infection. In controlled pollination frequency trials they found a strong correlation (r=0.87) between the percentage of unpollinated florets and ergot infection.

Downes and Marshall (1971) demonstrated in greenhouse experiments that night temperatures of 13°C or less during meiosis can induce male sterility in sorghum. Brooking (1976) estimated the critical stage for this to be 2-3 weeks prior to anthesis. The greatest temperature sensitivity was during the late archesporial cell—pollen mother cell development period, up to the leptotene stage of meiosis. Once meiosis progressed beyond leptotene, sterility was not induced. Development from microspore release through to fertilization was particularly insensitive to prolonged night temperature treatment. Inflorescences showing low temperature-induced sterility, developed anthers that were exserted normally at anthesis, but were only partially dehiscent. Pollen grains in these anthers at anthesis were mainly vacuolate, two-celled grains, equivalent to control pollen just prior to the onset of the maturation phase. In contrast, most of the control pollen was densely cytoplasmic and packed with starch grains.

The relationship between cold-induced sterility and ergot susceptibility was demonstrated by McLaren and Wehner (1992). In field trials with three male-normal sorghum genotypes, night temperatures <12°C, 3-4 weeks prior to flowering increased susceptibility to ergot to the equivalent of that of male-sterile genotypes. Seed set in noninoculated heads under pollination bags was also reduced, suggesting that increased susceptibility was the result of low temperature-induced sterility. Ergot incidence and seed set were inversely correlated (r=-0.92). Genotypes differed in their ability to tolerate pre-flowering cold stress, and in two of the three genotypes a progressive increase in sterility and concomitant increase in ergot was recorded from 16°C and below. This result is similar to cold induced sterility recorded by Brooking (1979), who suggested that the linear response of some genotypes to temperature reduction indicates that sterility is a quantitative response and not a qualitative one occurring below a critical temperature. Greenhouse and growth-chamber trials by McLaren and Wehner (1992) confirmed that cold stress applied 7-8 weeks after sowing reduced pollen viability, and that this was the primary reason for increased susceptibility to ergot.

Watkins and Littleficld (1976) studied ergot infection of wheat caused by *C. purpurea* and found an increase in ergot at low temperatures. They suggested that anthers may be sensitive to cool temperatures so that pollination is delayed and the ovaries remain susceptible for a longer period. Suneson (1937) reported the absence of functional anthers at flowering in wheat plants chilled from -3 to 2.5°C 1-5 weeks before they emerge from the flag leaf sheath. This could be the reason why pollination does not occur and ovaries remain susceptible to ergot for a longer period of time (Watkins and Littlefield 1976).

Brooking (1979) recorded some form of partial sterility in the hybrid CK60 x 606 at 25-20°C, as only 76% of the pollen grains were starched. Similarly, Thakur and Williams (1980) reported incomplete fertility restoration in F_1 hybrids of pearl millet as a factor reducing effective pollen availability and hence increasing ergot susceptibility in some hybrids. Pollen viability studies by McLaren (unpublished) suggest that this may be a major reason for differences in ergot escape resistance in sorghum lines. Only 5 of 58 lines evaluated showed 100% pollen viability despite minimum temperatures of <19°C during the period 3-4 weeks prior to anthesis. These

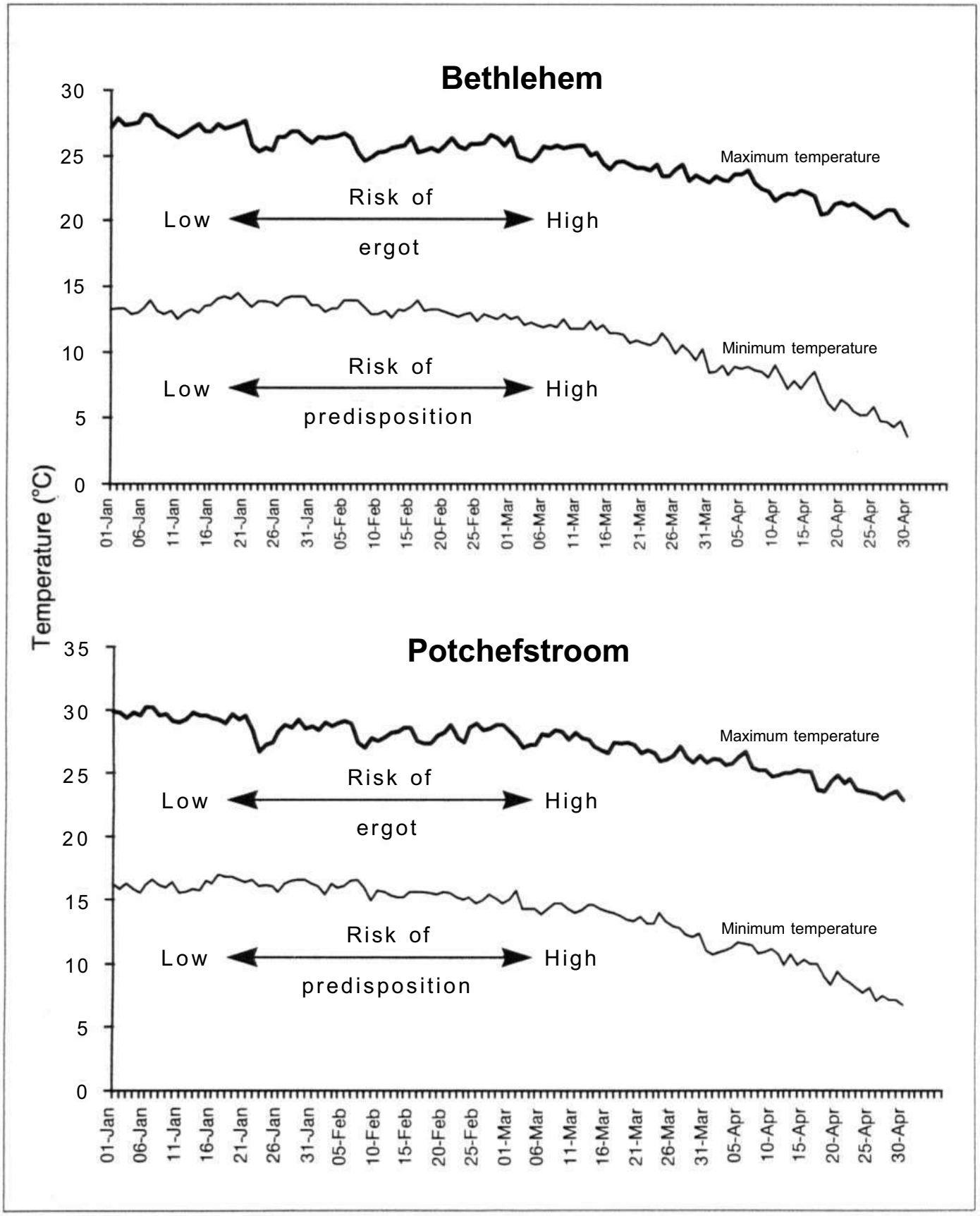

Figure 2. High and low ergot risk periods based on long-term daily maximum and minimum temperatures at two locations (Bethlehem and Fotchefstroom) in South Africa.

Local spread

Claviceps africana

Insect vectors, including moths and flies, have been linked with the local transmission of *Claviceps purpurea* and C. *paspali* (Langdon and Champs 1954, Moreno et al. 1970, Ingold 1971, Beerwinkle et al. 1993). *Claviceps paspali* is also transmitted by wind and rain (Noble 1936). The perfect stage of *C. purpurea* is formed readily and ascospores are known to act as infectious agents (Youngken 1947, Mantle and Shaw 1976). By analogy, the spread of sorghum ergot by wind-driven rain, mechanical contact and windborne ascospores has been assumed (Tarr 1962, Futrell and Webster 1966, Sundaram 1976), but without any real evidence. Instead Frederickson et al. (1989 and 1993) provide strong evidence for the role of windborne secondary conidia of *C. africana* in transmitting disease over moderate distances under natural environmental conditions in Zimbabwe. Secondary conidia are formed readily under natural conditions in southern Africa. In one experiment, an inoculated row of male-sterile sorghums exhibited prolific secondary conidiation of honeydew. Disease subsequently spread to panicles across several meters, a distance precluding physical contact, in one cycle of infection. Of 15 panicles protected from insects by fine-mesh netting, 14 became infected and germinating secondary conidia were observed on their stigmas. Using a spore-trap, secondary conidia were captured close to the panicles. In a second experiment, a disease source was created at the center of a 23.5 x 33 m area. The secondary conidiation of the source was apparently responsible for initial disease outbreaks up to 15 m away. Secondary conidia were trapped in air at this time. After one more cycle of honeydew production, when secondary conidia were even more abundant in the air, nearly all the panicles had become infected. Panicles protected from contact with large, flying insects became infected as did those in the first experiment. Secondary conidia were thus judged at least partially responsible for secondary spread. That rain occurred after the establishment of the initial outbreaks suggests that later spread may have been partially due to the distribution of honeydew by rain splash, although airborne secondary conidia were present at the same time. Frederickson captured macroconidia from the air during rain at panicle height and 0.75 m from infected panicles in a later study (unpublished).

Claviceps sorghi

In disease spread experiments similar to those of Frederickson et al. (1989 and 1993), Bandyopadhyay et al. (1991) attributed disease spread to water splash from sprinkler irrigation in rain-free situations. Their data show that in a male-fertile genotype, the proportion of infected plants in the total flowering plants d^{-1} increased from 40% 7 DAF to 100% 20 DAF. The number of infected spikelets $plant^{-1}$ increased from 40 to 180 in a similar time-frame (Bandyopadhyay et al. 1994a) indicating an increase in inoculum from secondary foci. There were 2-3 infection cycles, each of 6-8 d duration in a flowering season. From a point source, the disease spread over a 33 x 33 m field resulting in more than 25% plant infection. Ergot spread and focus formation was also mapped (Bandyopadhyay et al. 1994b). The spatial pattern of infected spikelets changed from a focal to a random pattern as the disease progressed through the distribution of macroconidia. Dispersal gradients obtained by fitting calculated dispersal data with power model, decreased over time. The Lloyd Index of patchiness for distribution of diseased spikelets also decreased as the disease progressed. The secondary foci appeared to be randomly established in the down-wind areas of the fields.

Long distance spread

The introduction of the disease in Brazil and Australia, and its spread within these countries offer good examples of the potential for long-distance spread. It also exemplifies the rapidity with which epidemics can spread to cover large geographical areas.

In Brazil, the disease was first noticed during mid-February in seed production plots in Sao Paulo state. Within one week, the disease was reported from Ribeirao Preto, Capinopolis, Lavras, Sete Lagoas, Pirapora, Paracatu, and Parana towards the north, and Xapeco (Santa Catarina state), and Pelotas (Rio Grande state) towards the south. The locations in Sao Paulo and Minas Gerais states where the disease was found surrounded an area approximately 800 000 km^2. The distance from Paracatu in the north to Pelotas the farthest point of infection in the south is nearly 2000 km. The magnitude of the area and distance covered by the pathogen within the short period of 1 week show the extraordinary capacity of the pathogen to spread rapidly in terms of both time and space.

Examination of weather data for Jan and Feb 1995 (provided by Dr O Brunini, Instituto Agronomico de Campinas, Campinas, Sao Paulo) showed that nearly twice the normal rainfall occurred in February in central and southern Brazil. The 25-day period before first report of occurrence of the disease in Ribeirao Preto (15 Feb) was extraordinarily wet. During this period, 446 mm rainfall occurred on 21 days. From 1-15 Feb alone, 343 mm of rain fell in 14 days. The predominant wind

directions at mid-day were north, northwest, and east. After 15 Feb, the predominant wind directions were south and southeast. Minimum temperature during mid-Jan to Feb was between 19-21°C and, therefore, not limiting for pollen production. However, the exceptionally wet conditions severely affected anther emergence, anther dehiscence, and pollen deposition. The inefficient pollination of male-sterile lines predisposed their stigmas to infection. The wet conditions and cloudy weather also provided an ideal environment for the continual production of abundant secondary conidia. Therefore, all the constituents for an epidemic were available at the same time—a susceptible host with an extended susceptible period, that was exposed to abundant inoculum of a newly introduced pathogen during favorable weather. A shorter incubation period, extended susceptible period, longer favorable period for infection and sporulation, and rapid transport of airborne secondary conidia aided several cycles of infection in the same area, and long-distance spread to newer areas. A reconstruction of *probable* events that led to the epidemic is as follows:

- Small foci of infection developed somewhere in south-central Brazil during 21-23 Jan.
- Secondary conidia produced in these foci were lifted in the cloud layer by convective currents (common during this part of the year) during 24-26 Jan.
- Traveling north with the clouds, secondary conidia deposited in the Ribeirao Preto area and further north with rain on flowering sorghum during the remaining days of Jan and early Feb.
- Initially in the newly introduced areas, few plants became infected and, by 7-12 Feb, produced numerous secondary conidia.
- Local and long-distance transport of these conidia helped to spread the extensive epidemics.

In Australia, the pathogen was first seen near Brisbane on 26 Apr 1996. Within 3 weeks, the disease became endemic in 60 000 km^2 of southern Queensland, and in northern Queensland in a much smaller area approximately 1500 km from the southern outbreak. The disease is now found throughout Queensland. Exceptionally cool and wet weather before and during flowering predisposed the sorghum crops to infection (M Ryley, personal communication).

The ergot pathogen in Brazil and Australia has been identified as *Claviceps africana,* the same as the one that is endemic in southern Africa and Thailand. Besides sorghum, ergot was also noticed for the first time in 1995 on pearl millet in Brazil. The pathogens causing ergot on sorghum and pearl millet are different. No one may ever know how the sorghum ergot pathogen was introduced to Brazil and Australia, despite strict quarantine. We can only hypothesize now:

- Sorghum seeds contaminated with ergot sclerotia from a *C. africana*-endemic region may have been illegally carried and sown in Brazil and Australia.
- Anyone walking through an infested field in a *C. africana*-endemic region, could have had their clothes smeared with honeydew, and/or brought back some soil (with macroconidia) on footwear. The same person perhaps walked into a sorghum field in Brazil wearing the contaminated clothes and/or shoes, thereby introducing the pathogen. Macroconidia can germinate on soil to produce secondary conidia which, being airborne, can infect sorghum.
- Due to an unusual intercontinental air current pattern from southern Africa to South America, secondary conidia could have been lifted from Africa to the cloud layer, crossed the Atlantic, and subsequently deposited in southern Brazil. This may sound science fictional, but explains why ergot appeared simultaneously on the two cereals in Brazil.
- Ergot could have been introduced into Brazil and Australia earlier than in 1995 and been present in low, undetectable frequencies. The exceptionally favorable conditions in 1995 (in Brazil) and 1996 (in Australia) could have helped the development of easily noticeable epidemics.
- A naturally occurring ergot pathogen on grasses may have undergone a change in virulence to diversify its host range to include sorghum. Initially, such an infection could have been in low proportion, but suitable weather helped development of an epidemic from a few small foci.

An understanding of the mode of introduction of the pathogen may help to devise methods to prevent its spread to new areas.

Survival of conidia in sphacelia/sclerotia

Sangitrao (1982) found that up to 16% sclerotia stored for 3 years were able to germinate by producing well-differentiated sexual structures and ascospores, and macroconidia in pionnotes. Macroconidia and microconidia can also survive in conidia in the dried honeydew on infected panicles that fall to the ground and remain viable for 7 months (Futrell and Webster 1966). Frederickson et al. (1991 and 1993) routinely used 9-12-month-old, dry-stored sphacelia of *C. africana* to generate inoculum for infection experiments. The initial resultant infections were few (usually only up to 10 sphacelia), but the honeydew had its normal infectivity restored following one passage through the host. Conidia from sphacelia stored

at 4°C or at room temperature, had equally low infectivity. Mower (1973) also used dried honeydew, stored at 5°C for 9 months, to infect sorghum.

Host range

There have been numerous reports on possible collateral hosts of *C. africana* and *C. sorghi.* The comprehensive list of Bandyopadhyay (1992) indicates that alternate hosts of *C. sorghi* include *Cenchrus setigerous, Ischaemum pilosum, Pennisetum orientate, Sorghum arundinacearum, S. caffrorum, S. halepense, S. membranaceum, S. nitens, S. verticilliflorum,* and *Zea mays,* whilst conflicting results have been reported for *Cenchrus ciliaris* and *Pennisetum typhoides* (Chinnadurai and Govindaswamy 1971b, Sundaram et al. 1970, Sundaram 1974). Recorded alternate hosts of *C. africana* are few to date. Futrell and Webster (1966) reported infection of *Zea mays* in Nigeria following artificial inoculation with *C. africana* conidia, but no infection of P. *typhoides.* However, conidia from *Panicum maximum* infected sorghum. This latter result is in accordance with Boon-Long (1992) but in disagreement with Frederickson, who could not infect sorghum with conidia from *P. maximum* in Zimbabwe. However, infection of several *Pennisetum americanum* varieties was successful. Conidia of ergot from *Cynodon dactylon, Urochloae brachyura, Brachiaria bryzantha, Digitaria tenata, Chloris guyana, Sporobolus pyrimidalis, Hyparrhenia* sp, and *Andropogon* sp, collected in South Africa, Zambia, and Zimbabwe did not infect male-sterile sorghum following artificial inoculation (Frederickson 1990). These results are not surprising because, according to Loveless (1964), the differences in size and shape of honeydew conidia on these grasses suggest that the pathogens are not *C. africana.* However, Sangitrao and Moghe (1995) reports that a triangular spore form of *S. sorghi* collected from *Dicanthium caricosum* could infect sorghum in India. Boon-Long (1992) reported infection of sorghum in Thailand with conidia from *P. maximum, Dicanthum annulatum, Brachiaria mutica, Sorghum sudanensis, S. almum,* and *S. halepense.* Only honeydew from a wild sorghum species in Zimbabwe, probably *S. versicolor,* has induced disease on cultivated *Sorghum bicolor* following inoculation.

In Japan, *Claviceps panicoidearum* from *Miscanthus* species can infect sorghum. Moreover, the teleomorph and anamorph show such a striking resemblance to *Claviceps* species (not *C. africana)* on sorghum that they may be the same organism (Tsukiboshi and Frederickson, unpublished).

Disease cycle

Primary infection in the field is probably established by conidia from collateral hosts and infected plant debris. Ascospores are also likely to serve as sources of primary inoculum. Based on field observations Singh (1964), Futrell and Webster (1966), and Sangitrao (1982) hypothesized that ascospores and conidia could infect collateral hosts that flower prior to sorghum, and that the conidia in the honeydew of collateral hosts provide fresh inoculum to initiate primary infection in sorghum. Infected spikelets exude millions of conidia in the honeydew which are spread by wind, rain, and possibly insects. In dry weather, well-differentiated sclerotia are produced and honeydew forms a hard white crust after the completion of the sporulation phase. In the following season, ascospores are produced from scierotia; conidia are produced from dried honeydew (Futrell and Webster 1966) or as pionnotes on germinating scierotia (Sangitrao 1982). Scierotia have internal locules in which macroconidia are produced and protected from the elements. With time, scierotia disintegrate and release macroconidia. These macroconidia can germinate on the surface of moist soil to produce secondary conidia. Secondary conidia are easily disseminated by wind and can initiate infection. However, the locule-macroconidia-secondary conidia hypothesis is still untested. The sexual and asexual spores subsequently infect collateral hosts, or may infect sorghum to complete the disease cycle.

Disease control options

Plant quarantine

Until recently, the disease has been successfully kept out of Australia. Australian quarantine laws require that all sorghum seeds imported for research or cultivation must be grown for one generation in a quarantine greenhouse, and be inspected by a qualified plant pathologist. The cordon of quarantine was, however, breached by an epidemic of the disease in Apr 1996. The strict quarantine regulations of the USA regarding sorghum ergot need to be strongly enforced to avoid entry of the pathogen into that country.

A standard protocol for the detection of *C. africana* in seeds does not exist and needs prompt development. Heavily contaminated seed lots can be recognized by an experienced eye following dry seed inspection, with dry white or orange-brown honeydew being evident on seeds or on sphacelia or scierotia. Small, spherical to conical sphacelia or scierotia, often with glumes still attached, can be seen among the more spherical seeds. Errors may have arisen in the past through quarantine officials failing

to recognize the small *C. africana* sclerotia when expecting the elongate sclerotia, typical of *C. sorghi,* as shown popularly in the literature. Following dry seed inspection a washing test may assist further. Seeds containing sclerotia, sphacelia or honeydew when ground and then agitated in very little water should release the distinct primary and secondary conidia of *C. africana* for verification under a microscope. The effectiveness of using a saline soak to float-out sclerotia of *C. africana* has not been demonstrated. Also, a method based on the detection of the sclerotial alkaloids of *C. africana* following extraction can be devised.

At ICRISAT Asia Center, quarantine regulations are followed rigorously to eliminate the possibility of exporting ergot-contaminated seeds. The protocol followed by ICRISAT is a simple one. The seed crop is normally grown during the hot and dry postrainy season with irrigation to avoid the disease. Seed lots are then physically cleaned to remove glumes, soil and other particulate matters. The Plant Quarantine Unit subsequently examines the seed lots under 10 x magnification for the presence of sclerotia. The seed lot is rejected if sclerotium is found. Then the lots are fumigated with methyl bromide (32 g m^{-3}) for 4 h. Finally, the seed is treated with a mixture of Benlate® and thiram (both are toxic to ergot conidia at very low doses) before despatch. However, the US quarantine regulations stipulate that seeds should not be treated with any chemicals. The chances of introduction of the pathogen through seed are minimized if the quarantine regulations are followed rigorously.

Host-plant resistance

Inoculation methods

Artificial inoculation methods must take into consideration the importance of flowering biology in disease development. It is inappropriate to inoculate spikelets after anthesis because fertilization interferes with infection. Evaluating flowers inoculated after pollination measures disease escape, rather than resistance. Essentially an inoculation method involves at least one artificial inoculation of nonpollinated spikelets and bagging of panicles (Musabyimana et al. 1995). Trimming of spikelets to remove all pollinated spikelets from a panicle before inoculation ensures that only nonpollinated spikelets are inoculated. Alternatively, inoculation of panicles on the first day of anthesis (Tegegne et al. 1994) or with approximately only 10% pollen shed (McLaren 1992) will achieve nearly the same objective without expending the time and effort required for trimming. Frederickson et al. (1994) selected panicles that had not flowered, inspected them daily in the morning, marked freshly anthesizing florets, and inoculated them with a spore suspension. Only the marked florets were subsequently used to measure disease. After inoculation, bagging enhances ergot severity by maintaining the high humidity that favors infection. Bagging also ensures that each panicle is tested without interference from external pollen, that could interfere with disease development. Furthermore, bagging facilitates production of selfed seeds, thus allowing direct selection of ergot-resistant plants.

Screening techniques

Hot spots. A hot spot is a location where environmental conditions are favorable and natural sources of inoculum are available for severe occurrence of the disease in most years. For ergot, such locations should have low night temperature and high humidity or wetness during preflowering and flowering periods during the growing season. The availability of overhead sprinkler irrigation to maintain high humidity for infection and pathogen spread is desirable, but not an absolute necessity. Hot spots have been used to effectively screen sorghum for ergot resistance at Arsi Negele in Ethiopia (Tegegne et al. 1994), Rubona in Rwanda (Musabyimana et al. 1995), Henderson and Panmure in Zimbabwe (Frederickson et al. 1994), and Bethlehem in South Africa (McLaren 1992). In India, sowing dates are adjusted such that preflowering and flowering periods occur when environmental conditions favor infection and disease spread.

Use of temperature gradients. The identification of resistance to ergot under artificially induced epidemics does not necessarily ensure that resistance will remain effective under natural epidemic conditions (Thakur et al. 1989). This is because ergot incidence in sorghum is extremely sensitive to changes in pre- and postflowering climatic conditions (McLaren and Wehner 1990 and 1992, Frederickson 1993). Desai et al. (1979) and Sangitrao et al (1979) showed a relationship between sowing date and ergot-favorable conditions during sorghum flowering. Early sowing tended to favor escape from the disease, whereas later sowing, that resulted in flowering during the cooler part of the season, promoted ergot incidence. Thus, in screening trials it is essential that the stability of resistance over a range of climatic conditions be quantified.

McLaren (1992) illustrated the need for temperature gradients in ergot resistance screening trials. Of 70 lines that failed to develop the disease at Potchefstroom in the warmer North West Province of South Africa, only three remained resistant when screened at Bethlehem, a cooler locality in the Free State. This was attributed to the

cooler conditions affecting the flowering pattern and pollination efficacy of sorghum genotypes. The extent of resistance breakdown also differed significantly between genotypes.

Preflowering cold stress reduces pollen viability in sorghum, thus reducing pollination efficacy and predisposing sorghum to infection by the ergot pathogen (McLaren and Wehner 1992). Genotypes differed in both cold sensitivity and the threshold temperature required to induce sterility.

McLaren and Wehner (1992) and McLaren (1992) created temperature gradients during the pre- and post-flowering periods by evaluating sorghum nurseries using a series of sowing dates at two localities. Individual heads of each genotype were marked with the date of onset of anthesis and artificial inoculation. This enabled subsequent graphic plots of ergot severity, seed set under pollination bags, and climatic conditions to be compared and gave indications of resistance and pollination efficacy under changing environmental conditions. Studies of this nature can also reveal significant disease-weather interactions that would otherwise not be recorded in single-sowing evaluation plots.

Self-pollination efficiency. The susceptible period for infection by the ergot pathogen is from stigma emergence to fertilization (Futrell and Webster 1965). Any factor that reduces pollination efficiency will therefore, increase susceptibility to infection.

The major factor contributing to reduced pollination efficiency is preflowering cold stress (McLaren and Wehner 1992), and it is therefore late-sown sorghum that is generally most severely infected. Preflowering minimum temperatures below 12°C reduced self-pollination in a tolerant hybrid (PAN 8564) to 21 %, as indicated by seed set under pollination bags. In contrast, seed set at higher temperatures was 80%. A concomitant increase in ergot incidence was recorded with decreased self-pollination efficiency. Pollen viability was reduced by 35-37% in susceptible hybrids, but only by 16% in a resistant hybrid in the greenhouse under a 25/10°C regime. Thus, differences in tolerance to preflowering cold stress is an important criterion in ergot escape resistance. Brooking (1979) found similar differences in genotype tolerance to cold induced sterility. In a sensitive hybrid, he found pollen sterility to be a linear response to night temperature with both 14° and 11°C lowering pollen fertility and thus, seed set. Molefe (1975) found ergot to be more severe in Botswana in fields associated with minimum temperatures of 14°C than in those that flowered during warmer conditions.

McLaren (unpublished) found differences in the rate of flower opening and self-pollination efficiency of sorghum lines. In a greenhouse trial male-sterile lines were inoculated with the ergot pathogen at various times after anthesis. Susceptibility to ergot lasted from 4 to 8 days, depending on genotype. Those panicles that were more efficient self-pollinators were more effective in escaping disease, as indicated in Fig. 3. A key aspect in efficient self-pollination is the rapidity with which fertilization occurs after pollination (Bandyopadhyay and Reddy 1991). There is a need to develop reliable and rapid methods of identifying efficient self-pollinators.

Jaster (1985) found a reduction in sorghum grain set with delayed anthesis of 3, 6, 9, and 12 days on male-sterile lines. Genotypes differed in the extent of these reductions. He also found that A-lines did not all start and finish flowering in the same length of time. The range from first to 100% anthesis averaged 4.2-6.4 days. Thus, even in the absence of ergot, inefficient or delayed self-pollination may induce permanent sterility. Whether this may promote ergot incidence needs more intensive study. Frederickson and Mantle (1988) found that if inoculation is delayed for 4 days after the florets 'gape', their Stigmas will cease to be a suitable substrate for the pathogen. In contrast, McLaren (unpublished) found that male-sterile lines remain susceptible to infection in the greenhouse for up to 16 days (Fig. 3). Bandyopadhyay (unpublished) also found that male-sterile lines could be infected by inoculating flowers up to 12 days after stigma emergence,

Chinnadurai et al. (1970a) reported that pollination of susceptible varieties with fertile pollen reduced spore germination, and hence host infection by the ergot pathogen. They attributed this to pollination affecting the nature of stigmatic exudates and subsequent effects on spore germination. Thus, rapid self-pollination may act as an inhibitor of pathogen development and play a role in reducing disease severity.

Frederickson et al. (1994) found that Rwandan and Ethiopian sorghums, resistant to ergot in their natural environments tended to be photoperiod-sensitive when grown in Zimbabwe, resulting in prolonged vegetative growth and ergot susceptibility. They suggested that the resistance expressed in their natural environments resulted from efficient self-pollination, that allowed insufficient time for colonization of the ovary by the slower growing pathogen. Their photoperiod-sensitivity in Zimbabwe could have affected this balance in these accessions. One accession, IS 25485 however, remained disease-free. Examination of the florets of this genotype showed that cleistogamous pollination had occurred in a large percentage of the florets 1 day before the flowers

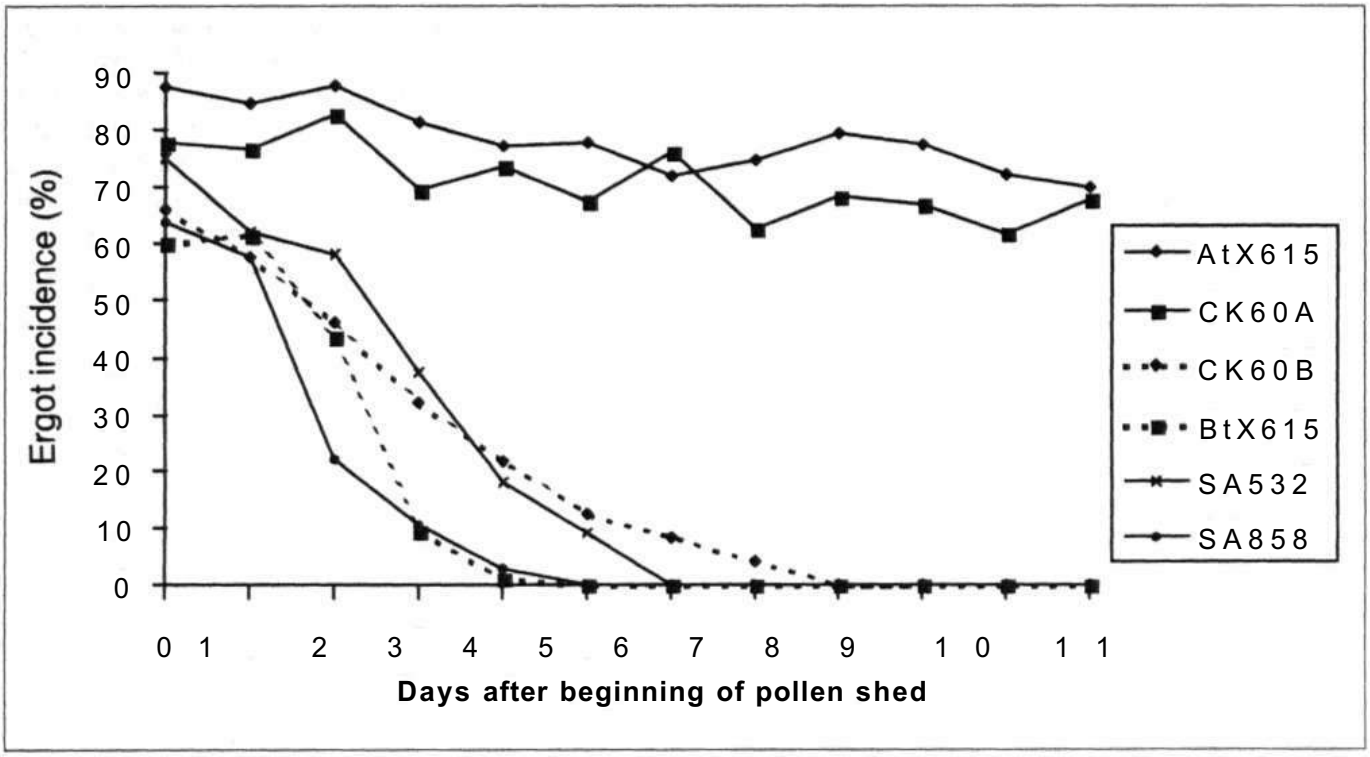

Figure 3. Ergot incidence in male-sterile and male-normal sorghum lines inoculated at various times after pollen shed.

gaped. By the time of floret gaping and artificial inoculation with the ergot pathogen, pollination had occurred, and disease escape was complete.

Evaluation procedures

Disease evaluation. Different procedures have been followed by various researchers to measure ergot in disease-evaluation trials. Disease has been measured qualitatively by visually estimating the proportion of panicle area infected (Anahosur et al. 1990), or the percentage of flowers infected (McLaren et al. 1992, Musabyimana et al. 1995), or disease expressed on a 1-5, or 1-9 scale. Frederickson et al. (1994) quantitatively measured disease incidence by counting the proportion of diseased panicles, and disease severity by counting the proportion of inoculated flowers that became infected. Tegegne et al. (1994) and Musabyimana et al. (1995) sampled one primary branch from each node of the rachis, counted the number infected flowers in the composite sample, and determined the proportion of infected flowers in the panicle. The visual, qualitative method underestimates disease in a panicle because some infected flowers are not visible on the single plane of the panicle or because sphacelia and sclerotia may be concealed in the glumes. However, since it is rapid and simple, this method can be used to reject susceptible lines in large screening trials. Quantitative evaluation is tedious and time-consuming, but is appropriate in trials requiring accurate data. Tegegne et al. (1994) suggested that both quantitative and qualitative methods can be used in resistance screening trials. The qualitative method can be used in the field to make a first rapid evaluation of large number of entries. After rejecting panicles with susceptible scores; the ratings of other panicles can be confirmed by quantitative evaluation. Tegegne et al. (1994) and Musabyimana et al. (1995) used both methods in trials to identify sources of resistance.

Sangitrao (1982) measured sphacelial and sclerotial phases of the disease separately by rating individual panicles qualititavely on a 0-5 scale, where 0 = no ergot, 1 = 1-20 (or 0.05 to 1%) infected spikelets in a panicle, 2 = 21-50 (or 1.05 to 2.5%) infected spikelets, 3 = 51-100 (or 2.55 to 5%) infected spikelets, 4 = 101-500 (or 5.05 to 25%) infected spikelets, and 5 = 500 (or 25%) infected spikelets. The rating scale was pictorially depicted using a standard area diagram. He evaluated at least 50 panicles plot^{-1}, and expressed ergot severity as the percentage disease index (PDI), calculated by dividing the product of the total rating of all panicles and 100, with the product of the total number of observed plants and the maximum rating (5).

Seed set Frederickson (1993) found that seed set in inoculated R-lines was higher at 25°C than at 20°C or 30°C. She suggested that pollination and seed set have the competitive advantage over ergot at 25°C. Reduced seed set at 30°C may have been heat induced, although at this temperature disease development is known to be restricted (Frederickson 1993, McLaren and Wehner 1990).

McLaren and Wehner (1992) found seed set under pollination bags to be correlated with preflowering cold stress. The induced sterility was highly correlated (r=0.92) with ergot incidence. Genotypes differed in their seed set x cold stress interactions, with concomitant differences in ergot severity. Bandyopadhyay and Reddy (1991) came to a similar conclusion based on concurrent, but similar studies with a different set of maintainer lines from those of McLaren and Wehner (1992).

In pearl millet, Thakur et al. (1983) found that ergot infection in hybrids was positively correlated with grain yield. The increase in grain yield was attributed to the effects of rapid pollination resulting in seed set which would otherwise be lost to ergot.

Care needs to be taken when using seed set as an evaluation criterion. Frederickson et al. (1994) found that Rwandan and Ethiopian lines resistant to ergot in their native environments showed photoperiod-sensitivity when evaluated in Zimbabwe. This was accompanied by a reduction in seed set in most accessions. Despite sterility, some accessions failed to become infected. Frederikson suggested that gynoecial formation was abnormal in the different environment, or that in this environment gynoecia were unreceptive to both pollen and the pathogen. For this reason, undue emphasis on seed set as an indication of predisposition to ergot may skew the results of ergot evaluation trials.

Regression methods. Sundaram (1980) suggested that in order to compare ergot severities in breeding lines, particularly those differing in seasonal requirements, sowing dates must be adjusted so that plants will flower, and can be inoculated at the same time. In most semi-arid regions climatic cycles are unpredictable and synchronous flowering in desired climatic conditions is virtually impossible. Furthermore, temperature variations of relatively small magnitude before flowering and during the first 4 days after pollen shed significantly affect ergot incidence (McLaren and Wehner 1990 and 1992). This, together with natural variation in flowering dates both within and across sorghum genotypes, has resulted in inaccurate comparison of ergot incidences. The extent to which the differences in disease incidences reflect the host genotype, or the result of differences in climate associated with differing flowering dates is questioned.

McLaren (1992) used regression analyses to quantify the resistance of sorghum genotypes to ergot. An advantage of this method was that ergot severity in sorghum genotypes that flowered at different times could be statistically compared. Temperature gradients were created by sowing nurseries at two locations over a range of sowing dates. At flowering, individual heads were marked with the date of anthesis and artificial inoculation. Ten heads genotype^{-1} were inoculated on 3 to 4 different dates at each location. Visual estimations of percentage infected florets head^{-1} were made and these values were used to calculate the mean ergot severity genotype^{-1} associated with each inoculation date. An index of ergot-favorable conditions was determined, as the mean disease incidence over all genotypes associated with a specific flowering date. This was termed the disease potential, or expected disease severity, associated with a specific flowering date.

Non-linear regression analysis, using the model $Y=ax^b$ was used to determine the relationship between ergot potential associated with different inoculation dates and observed disease incidence within genotypes. Lines could be classified into three categories; those linearly related to disease potential, those highly susceptible (even at low disease potentials), and those with various degrees of resistance despite increasing disease potentials (Fig. 4). Genotypes in the latter group differed with-respect to resistance breakdown points. The latter was defined as the disease potential required to induce 5 % or 1 % disease severity (termed 5% or 1% breakdown point) and could be calculated by substitution into the regression model. Re-arrangement of the regression model also enabled the subsequent rate of resistance breakdown at any point to be calculated. These criteria proved to be useful for quantifying resistance as they are fixed values, independent of fluctuations in flowering dates and variations in climatic conditions during flowering and infection. A disadvantage, however, is that large, diverse populations are required to allow the calculation of ergot potentials for different flowering dates. McLaren (in preparation) has developed a method of estimating disease potential based on climatic variables prior to, and during flowering. This will enable the breakdown points of smaller nurseries to be determined without large diverse populations being required for disease potential determinations.

Sources of resistance

Bandyopadhyay (1992) stated that the lack of confirmed sources of resistance to sorghum ergot underscores the urgent need to identify ergot resistance sources. Many

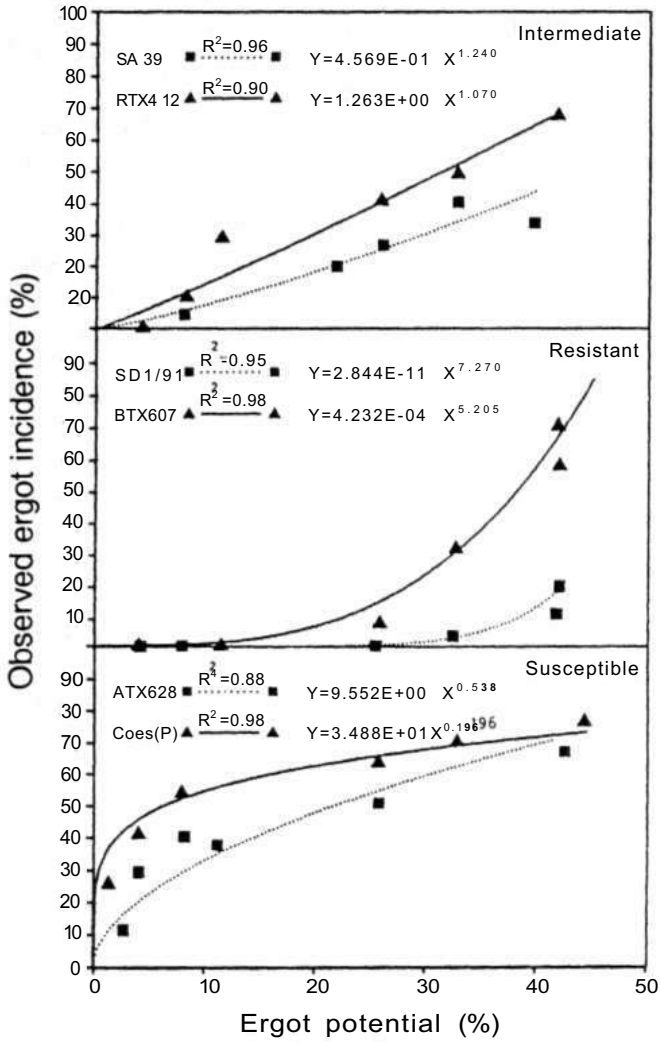

Figure 4. Illustration of three relationships between ergot incidence in sorghum lines and ergot potential using the regression model $Y = ax^b$.

reports of resistance to ergot have been made on sorghum (see Table 2). However, as pointed out by Tegegne et al. (1994) most reports are based on the results of unreplicated trials and many lines previously reported resistant have proved to be susceptible in subsequent trials and at other localities (Frederickson et al. 1994). McLaren and Wehner (1992) and McLaren (1992) showed that, given the correct preflowering predisposition and climatic conditions during early flowering, all genotypes are probably susceptible to ergot. For example, the sorghum lines found resistant to ergot in Ethiopia were susceptible in Rwanda, and vice-versa (R Bandyopadhyay unpublished). Since G x E interaction is critical for disease development, it is necessary to qualify resistance in particular lines with respect to the limits of environmental conditions in which it is operable. As a first step, it is necessary to retest the lines reported as resistant and quantify their resistance using the method described by McLaren (1992).

Genetics and mechanisms of resistance/susceptibility

Even early reports on sorghum ergot outbreaks recognized that cytoplasmic male-sterile or A-line sorghum cultivars were highly susceptible to ergot, whereas the B-lines, R-lines, and other male-fertile varieties had low susceptibilities (Futrell and Webster 1965 and 1966, de Milliano et al. 1991). As with other ergot pathogens and their hosts, the primary reason for susceptibility is the delay or failure of pollination, so that even male-fertile varieties can become susceptible during or following weather conditions that reduce pollen fertility, or retard and reduce pollination (Puranik and Mathre 1971, Done 1973, Watkins and Littlefield 1976, Brooking 1979, Thakur and Williams 1980, Wood and Coley-Smith 1980, Thakur et al. 1983, Thakur et al. 1989, McLaren and Wehner 1990, McLaren 1992b). Normally, following pollination of the stigma, the post-fertilization, ultrastructural changes in the gynoecium prevent the subsequent invasion of ergot hyphae by the same pathway. In sorghum, infection by *C. africana* was close to zero 48 h post-pollination (Musabyimana et al. 1995). The extreme stigma constriction phenomenon in pearl millet gynoecia after the passage of pollen tubes down stylodia, similarly excludes *C. fusiformis* (Willingale and Mantle 1985 and 1986). Frederickson et al. (1994) found that rapid, even cleistogamous, pollination was responsible for the resistance of Ethiopian and Rwandan sorghums tested in Zimbabwe *C. africana* under natural and artificial disease pressure. Because of this inverse relationship with pollination, extensive screening of sorghum for resistance to *C. sorghi* and *C. africana* has failed to provide a resistant male-sterile sorghum (Ajrekar 1926, Chandrasekaran et al. 1985, Rajkule et al. 1985a and 1985b, Bandyopadhyay 1992, McLaren 1992a, Frederickson et al. 1994, Tegegne et al. 1994, Musabyimana et al. 1995).

Screening for resistance is complicated by the differing sensitivities of genotypes to environmental conditions (see Effect on environment on pollination, infection, and their interactions). Field studies by McLaren and Wehner (1990 and 1992) and McLaren (1992b) with *C. africana* in South Africa clearly show that ergot disease incidence increases if maximum temperatures are below 12°C at flowering, with optimum disease intensity at a 19.5°C maximum. There may also be interactions with hours of sunshine and rainfall. Minimum temperatures below 12°C at 3-4 weeks prior to flowering and in the 4 days

Table 2. Sorghum lines reported to be resistant to sorghum ergot.

Genotypes	Reference
SPV 126 and SPV 232	Rajkule et al. 1983
IS 2205, 4358, 5125, 5687, 5689, 7960; Ms 7999, 8030, 8268, 8289; As 6142, SOR 766; and SOR 831	Lakshmanan et al. 1988
SPV 617 (SPV 671 is susceptible)	Chandrasekaran et al. 1985
SPV 671, 677, 683, 686, 698, 351; 695, 696, and 697; SPH 329, 332, 341, 342, and 346; and MSH 56	Rajkule et al. 1985b
IS 625, 2867, 3413, 8101, 8545, 8614, 14332, 14380, and 14387	Rajkuleetal. 1985a
SPV 59B, 220, 224, 260, 35, 300, 138, 233, 289, 295, and 296	Kukadia et al. 1982
SB 1085, 2413, 2415, 5501, and 1079; IS 2217, 2328, 3443, 3547', 8283, 14332, and 18758; M 35610; CSV 4	Anahosur and Lakshman 1986
IS 25480, 25527, 25530, 25531, 25533, 25537, 25551,25554, 25555, 25570, 25576, and 25583	Musabyimana et al. 1995
ETS 1446, 2448, 2465, 3135, 4457, and 4927	Tegegne et al. 1994
SA 1304, SD1/91, SA 1619, SA197; RTAM 428, and 29 others	McLaren 1992
Tunis grain, G 4, and Sumac	Singh 1964
ETS 3252, 3251-1, 4145, 4457, 4927, 2448, 3125, 3912, and 1446; IS 25542, IS 25576, IS 25555, IS 25485, 83/8/1/1, 83/54/4/2-2, 83/54/1/2, 83/42/1/1, 12192, and TURA	Frederickson et al. 1994
IS 2495, 5337, 6449, 6705, 6891, 7584, 8051, 8070, 8609, 8930, 8936, and 9091	(C S Sangitrao, personal communication)
K.3, *S. nodulosunu* IS 1122, IS 5285	Chinnadurai et al. 1970b
J-604, M 35-1, and M 47-3	Khadke et al. 1978
IS 2444, 4530, 5285, 3248, 8970, and 7239	Sundaram 1970
CO 25, CO 23, TNS 23, TNS 28, TNS 35, TNS 24, TNS 30	Lakshmanan and Mohan 1989
IS 14332, IS 3443, and IS 3547	Anahosur et al. 1990
MS 7960, 8030 and others; IS 2205, 5125, 4358, 4006, 4300 and others; SOR 831, 766 and others; AS 6142 and others	Lakshmanan et al. 1987

1. Also resistant to sorghum downy mildew, ehareoal rot, grain mold, rust, zonale leaf spot, and anthracnose.

after pollen-shed, induce pollen sterility, resulting in increased ergot infection. Screening methods which therefore fail to consider the differing temperature sensitivities of genotypes lead to inaccurate ergot disease incidence comparisons. Environmental sensitivity also means that cultivars must be locally adapted to ensure the stability of their resistance. Comparing 'sugary disease breakdown point'(SDBP), the disease level required to produce 1% ergot severity in genotypes, and breakdown rate (rate at which disease reaches 1%), circumvents this problem

(McLaren 1992), allowing accurate comparison of disease in genotypes with different flowering dates grown at different localities, and in different seasons. Given the critical interactions outlined, it would seem logical to search for R-lines with increased cold tolerance in microsporogenesis and in pollen germination, and for A-lines exhibiting a fundamental physiological gynoecial response to limit infection. Apart from one study by Frederickson et al. (1994) in which the accession IS 25570 with poor seed set and low *C. africana* severity exhibited a necrotic reaction at the mid-point of its styles, studies to date reiterate that resistance is in reality 'escape' through pollination.

Breeding for resistance

Bandyopadhyay (1992) suggested that resistant cultivars are probably the most practical and economical method of ergot control, but also pointed out that lines with significant and stable levels of resistance were not available. This is consistent with a report by Willingale et al. (1986) who stated that, despite *Claviceps* sp occurring on many graminaceous crops, there is no consistent evidence of physiological sources of resistance in any of the crops that ensures protection against the particular *Claviceps* spp that parasitizes that crop plant.

Because there is no physiological resistance to ergot, attention should be given to indirect or escape resistance. This has proved particularly useful in breeding for ergot control in pearl millet. Willingale et al. (1986) found that ergot-resistant lines possess very short periods of protogyny and could relate ergot severity to the length of protogyny and rate of self-pollination. In a few cases, millets were protandrous with a concomitant increase in pollination rate and escape resistance. Although not so extensively studied, similar variations in sorghum flowering patterns exist, and floral characteristics that promote pollination should be selected. IS 25485 from Rwanda is such a line. As described by Frederickson et al. (1994), this line is characterized by cleistogamous pollination and efficient self-pollination before gaping, such that insufficient time for colonization of the ovary by the pathogen is allowed. As a result, this line remained resistant over a range of localities, from Rwanda to Zimbabwe.

McLaren and Wehner (1992) studied cold tolerance in sorghum hybrids. The hybrid PAN 8564, that was more cold-tolerant than other hybrids, was less susceptible to preflowering cold-induced sterility, and hence more efficient at self-pollination, seed set, and ergot escape. Brooking (1979) in New Zealand found the line 606 to be particularly resistant to preflowering cold stress with normal pollen in cold-stress regimes of 25/5°C. Data suggested that selection for tolerance to cold-induced sterility can contribute to ergot escape resistance.

McLaren (unpublished) found significant differences in the rate of flower opening, self-pollination, and length of the ergot susceptible period (Fig. 3). Flowering and the concomitant ergot susceptible period in SA 858 lasted for 5 days as opposed to 8 days in CK 60 B. This results in a risk period reduction of 37% in SA 858 compared with CK 60 B. Thus, selection for rapid reduction of the ergot-susceptible period can contribute to integrated ergot risk reduction.

Chinnadurai et al. (1970b) found that the varietal reactions of sorghum were related to the nature of stigmatic secretions. Susceptible cultivars secreted large amounts of substances which stimulated spore germination, including malic acid, succinic acid, arginine, and aspartic acid; whereas resistant cultivars secreted tartaric acid and tyrosine that were inhibitory to spore germination. Kannaiyan et al. (1973) found a similar mechanism in pearl millet resistant to *Claviceps fusiformis,* with tryptophane as the spore germination inhibitor. Thus, identification of inhibitor substances (notably certain amino acids) and selection of genotypes with high levels of inhibitory substances can contribute towards resistance to, or escape from, ergot.

Hassan et al. (unpublished) found that secondary sporulation was less in the exudates of high-sugar (sweet) sorghums was restricted than in those of grain sorghums. No apparent differences in the severity of infection in sweet and grain sorghums were recorded. However, reduction in secondary sporulation, and the resultant reduction in inoculum levels could have an epidemiological significance and contribute to integrated ergot control.

McLaren (unpublished) found significant differences in male:female compatibility of sorghum. A poorly compatible relationship between pollen and stigmatic tissues prolongs the period from flower opening to fertilization and hence the length of the ergot-susceptible period. Conversely, good compatibility will promote ergot escape resistance. Jaster (1985) found that pollen x stigma compatibility in ATx 623 was the best he tested based on the percentage of pollen tubes in the ovary (32%) 60 min after pollination, with ATx 399 (17%) and ATx 3197 (23%) were the least comparable.

Thus, it is evident that although physiological resistance to ergot is lacking, or yet to be identified, many minor floral characteristics could, if selected for, contribute to ergot escape resistance. The breeding strategy to incorporate ergot resistance in sorghum should rely on traits that allow rapid pollination and fertilization in environments favorable for disease development.

Very little has been published on the genetics of ergot resistance in any graminaceous crop except pearl millet. Thakur et al. (1989b) showed that ergot resistance in pearl millet is controlled by polygenic recessive genes implying that to breed ergot-resistant hybrids, resistance should be incorporated into both male-sterile and pollen parents (Rai and Thakur 1995). The greatest need is to identify ergot-resistant male-sterile lines, although the chances of identifying, or breeding ergot-resistant male-steriles appear slim in view of the role of pollen in disease development. However, ergot-resistant male-sterile lines of pearl millet have been developed (Thakur et al. 1993) suggesting that it might be possible to develop ergot-resistant male-stcriles in sorghum too. Ergot-resistant maintained, restorers, and hybrids of pearl millet have also been bred (Thakur et al. 1993). Futrell and Webster (1965) reported that in screening trials, sorghum lines with cytoplasmic sterility were more susceptible to ergot than sterile lines due to chromosomal aberrations: McLaren (unpublished) in preliminary trials compared isogenic lines of 'Martin' with A_1, A_2, A_3, and A_4 cytoplasm, and found that the A_4 cytoplasm tended to be less susceptible to ergot. Although of no immediate economic value, these results suggest that cytoplasm may be a factor in ergot susceptibility, and that evaluation of alternate cytoplasms in relation to ergot susceptibility is warranted.

Chalal et al. (1981) screened pearl millet germplasm under epiphytotic conditions and found a total lack of major gene resistance to *C. Jusiformis,* They pursued a strategy involving recurrent selection to concentrate the minor genes controlling polygenic resistance for intrapopulation improvement. Inbred lines with less than 5% ergot severity were selected and intermated to produce two diallel populations. After 3-4 cycles of recurrent selection the proportion of plants with 0-5% severity increased, indicating that an appreciable level of resistance can be successfully generated. Similar studies have yet to be conducted on sorghum. Good progress has been made in breeding for ergot resistance in pearl millet and there is much to learn from the well-documented extensive research on pearl millet ergot conducted at ICRISAT (Thakur and King 1988, Thakur et al. 1993) during the 1980s and 1990s.

Cultural methods

Adjustments in sowing date and location

In Zimbabwe, farmers claim that sowing early in November (when permitted by the season), results in ergot infecting only tillers, perhaps partially because microsporogenesis occurs well before minimum temperatures fall to below 12°C, or A-line flowering coincides with a mid-season dry spell. Since severe ergot epiphytotics, resulting in nearly total seed loss, occur every 5 years on sorghum A-lines in Zimbabwe, sowing adjustments clearly give only limited control. This is re-emphasized in studies by Frederickson (unpublished). In India, sowing in early July in preference to early August also resulted in reduced *C. sorghi* infections (Sangitrao et al. 1979, Anahosur and Patil 1982) because plants flower at temperatures favorable to rapid pollination and fertilization.

Although most of the seed companies in India are located in Maharashtra, F_1 hybrid seeds are rarely multiplied there because of the risk of ergot. Most of the sorghum seed is produced in Andhra Pradesh under irrigation in the dry season areas (e.g., Telangana) where environmental conditions are not favorable to ergot attack. In Zimbabwe, seed production plots in the Muzarabani area usually escape ergot infection. However, ergot is able to infect male-sterile sorghums virtually wherever and whenever they are grown in southern Africa provided that environmental conditions are favorable, be it on research stations or in commercial fields (W A J de Milliano, personal communication). Neither production in a dry area, nor irrigated production in the dry season guarantees escape from ergot.

Reduction of inoculum

Farmers who produce hybrids in Zimbabwe remove infected panicles from the field at harvest, plow residues into soil, and practice crop rotation (Swift and Hurrell, personal communication). These precautions would appear to be reasonable, but are without obvious effect, perhaps due to the ability of the pathogen to spread rapidly by secondary conidia from a small focus of infection (Frederickson et al. 1993). Even though germination of *C. africana* sclerotia, and thus ascosporic infection, is probably a rare event in nature, sclerotia would have very low infectivity at only a few centimeters of soil depth (Anonymous 1972). Nevertheless, sowing seeds free from sclerotia will eliminate the possibility of introducing the disease into new areas. Sphacelial conidia of C. *africana* can live for 9 months in panicles maintained at the field surface between crops (Frederickson, unpublished). Macroconidia on such residues may possibly germinate to produce airborne secondary conidia for the initiation of new-season infections, and plowing would again reduce initial inoculum sources. Although the ascosporic stages of *C. sorghi* and *C. africana* have not been confirmed in nature, removal of contaminating sphacelia and sclerotia from seed batches is advised. In

India, seeds are soaked in water and sclerotia floated-off in 5% salt solution, followed by seed drying (Bandyophadhyay 1992). The same practice has been attempted in South Africa, with only slight loss in seed viability (McLaren, unpublished). However, all these practices will remain arbitrary as control measures, until the source(s) of initial inoculum is determined.

Pollen-based management

Poor 'nicking', or nonsynchrony of flowering in male-sterile lines and restorers, and lack of viable pollen during stigma emergence are the major reasons for the increased susceptibility of male-sterile lines in seed production plots. Efficient pollination reduces the window of infection, i.e., the time between stigma emergence in male-sterile lines and pollen shed by restorers, and is the most effective strategy to significantly reduce ergot damage. In Zimbabwe, farmers routinely stagger the sowing of the pollen-donating R-lines, sowing the first R-line row 7-10 days before the second row and the A-lines, to ensure a more regular supply of pollen to the A-line (Hurrell and Swift, personal communication). This gives mixed success in reducing *C. africana* ergot infections, because of the more critical effect of the environment around the time of flowering (McLaren and Wehner 1990, McLaren 1992). Frederickson and Obilana (1993) evaluated pollinator:female ratios in field trials. Seed set was more variable between rows with a 6:4 (A:R line ratio than with a 4:4 layout. Highest seed set was found in rows adjacent to the pollen source. Furthermore, disease increase was more rapid in 6:4 ratio plots than in the 4:4 layout. Similar results were recorded by Thakur et al. (1983), who found a significant decrease in ergot of pearl millet caused by *C. fusiformis* with pollen donor:female ratios of 1:2 compared with 1:4, and 1:8.

Control with fungicides

It is uneconomical for small-scale farmers but acceptable for seed producers to use fungicides to control ergot. Appropriate fungicides sprayed at stigma emergence stage and at 5-7 day intervals has been shown to reduce the disease. The control is good if inoculum pressure is low, and in the absence of rains; but disease control is not absolute at high inoculum pressure. Fungicides do not have curative action, and are most effective as preventive measures. Therefore, sprays should begin before the onset of the disease in the field, and continue until flowering is complete, they have little effect after the onset of the disease.

Fungicide control of *C. sorghi* has been extensively investigated (Nagarajan and Saraswathi 1971, Gangadharan et al. 1976, Sundaram 1976, Anahosur 1979, Lakshmanan et al. 1986), less so for *C. africana* (McLaren 1994). In India, 2 or 3 sprays of.0.2% Ziram®, thiophanate methyl, and Captafol® at 2-week intervals starting at the boot stage increased yields from 1 to 4 t ha^{-1}. Other fungicides including thiram, Ziram®, zineb, and Dithane-M45® were also effective. Nagarajan and Saraswathi (1971) obtained little field control of *C. sorghi* with the systemic fungicides Benlate®, Plantvax 75W®, Vitavax 75W®, and Tecto 60®. This is true in field situations when disease pressure is high, but control is usually good if inoculum pressure is low. McLaren (1994) controlled *C. africana* in South Africa using one of several systemic fungicides (benomyl, carbcndazim/flusilazol, propiconazole, triadimenol, terbucanazole and CG169374) but bitertanol at 150 or 300 g a.i. ha^{1} and procymidone at 250 g a.i. ha^{-1} gave significant disease reductions. However, McLaren calculated that yield gains were not sufficient to justify economic use of fungicides. In Zimbabwe, Frederickson and Leuschner (unpublished) found that benomyl at 0.2% a.i. reduced ergot disease significantly in A-lines if sprayed once at heading, and calculated that control was economically feasible. The use of fungicides would be invaluable for the production of hybrid seed even though control may not be absolute. Fungicides normally used do not have male gameticidal effect, and thus seed set should not be affected. Much research on fungicidal ergot control is currently in progress in Brazil and Australia. Fungicide use by seed producers in Brazil reduced losses due to the disease in 1996.

Dressing of seed with thiram (1:250) was recommended by Sundaram (1976) to prevent sclerotial germination. Mantle and Hassan (1994) recommend seed treatment as a routine precaution to prevent the entry of seedborne *C. africana* into the Americas, but did not suggest a specific fungicide. Except for Sangitrao (1982) who found that fungicidal seed treatment reduced, but did not prevent, sclerotial germination, no other information is available on the toxicity of fungicides to sclerotia. Neither is it known if fungicides can penetrate sclerotia to kill conidia embedded in internal locules. *Claviceps purpurea* sclerotial germination is limited following seed treatment with triadimenol, a chemical that may have a potential use against *C. sorghi* and *C. africana* sclerotia. In Brazil, triadelmenol applied as a spray has been found effective in reducing disease in the field.

Adjustments in seed processing plants

Removal of sclerotia from seed harvested from affected fields during seed processing may be a useful strategy.

During the seed-cleaning process, a gravity table aided by an air-stream could effectively separate sclerotia that are lighter in weight than normal seeds. However, further research on this technique is required. The use of salt water solution to float out sclerotia is not practical in seed-processing plants because such a treatment would increase the seed moisture content at a stage when the seed needs to be dried.

Integrated ergot management strategies

Although ergot is of greater consequence in hybrid seed production fields, damage in commercial grain crops is also often significant in pollen-limiting environments. The approaches to ergot management in hybrid seed production and grain production require different emphasis on the various components. Pollen-based management, ergot escape, chemical control, and removal of sclerotia in seed-processing plants are of overriding importance in the production and processing of hybrid seeds. Host-plant resistance is most likely to succeed economically in grain production plots. In both production situations, the use of methods that reduce inoculum in the field are relevant in reducing damage. Further research is essential to test combinations of different components of ergot control to develop integrated ergot management strategies to suit the socioeconomic and technological needs of each location and end user.

Research needs

Considerable research information is available on the infection process, role of pollination and fertilization on disease development, and techniques to screen for resistance. Future work should build upon past research in developing integrated ergot management (IEM) practices. Thus, the future thrust of research should be directed toward strategic research on pathogen biology, disease epidemiology, and on components of IEM practices.

Biology

- Identify the species of *Claviceps* prevalent on sorghum in different parts of the world and determine relationships among these species, if any.
- Re-examine the taxonomy in *Claviceps* spp that attack sorghum using large samples of the pathogen population from different areas.
- Develop simple and rapid detection methods for sclerotia/ sphacelia in seed for use by quarantine officials to prevent entry of *Claviceps* spp into disease-free countries via contaminated seed, and by seed quality laboratories to certify pathogen-free seed. Since *C. africana* has elaborate sclerotial alkaloids, direct chemical analysis for alkaloids may be appropriate. Alternatively an immunological technique could be developed as was done recently for C. *purpurea* (Shelby and Kelley 1992). This latter method may also be appropriate for sphacelia. Effective ways to establish the identity of *Claviceps* spp in seed lots need to be developed.

Epidemiology

- Determine sources of initial inoculum, especially with respect to preventing entry of the pathogen into disease-free countries. Possible sources include sclerotia (ascosporic infection and conidia) and sphacelia (macroconidia on internal fructifications, secondary conidia).
- Find the alternate hosts of the pathogen and determine their role in the epidemiology of the disease.
- Determine the role of sclerotia as a source of primary inoculum. Further explore the possibility of sclerotial germination by sexual means under natural conditions. Also, study the prospect of the following mechanism for the survival and initial spread of the pathogen: thick-walled sclerotia over seasons protecting macroconidia contained within their locules from edaphic elements; the sclerotial wall slowly degrades with the onset of rains thereby releasing macroconidia on the soil surface; macroconidia germinate on moist soil to produce secondary conidia; secondary conidia become windborne and initiate primary infection in the field. Also, study the longevity of macroconidia in soil, and the possibility of the process described above occurring in the absence of macroconidia protected within the locules of sclerotia.
- Focus investigations on the relationship between temperature and longevity and infectivity of conidia, and the conditions under which primary conidia on field residues produce secondary conidia.
- Conduct studies to find the environmental factors leading to secondary conidiation and the release of secondary conidia into air; germination and longevity.
- Determine the length of survival of sclerotia in different environments and quantify the extent of sclerotia seed contamination that is necessary to spread the pathogen.
- Ascertain if seed contaminated with conidia serve as a source of primary inoculum in the field (it is generally believed that seedborne conidia are not sources of primary inoculum).

- Determine the effect of different environmental conditions on flowering biology, infection, and their interactions to better understand factors influencing disease incidence.
- Develop a statistical model to predict the occurrence of disease using data on weather (temperature, humidity, rainfall, solar radiation, etc.), host (pollen production and viability, stigma receptivity, nicking, etc.) and disease incidence. Such a model could help to forecast the occurrence of the disease and to better schedule and optimize fungicidal spray application.

Components of management practices

- Develop a spray schedule of effective fungicides with details of timing of application, requirement of stickers, frequency and dose of application, volume of spray water required, and economics for the practical control of the disease. Also, suitably modify spray equipment to avoid damage to plants.
- Determine the effect of seed treatment with fungicide on the viability of sclerotia and the conidia contained in seed, and on conidia contaminating the seed surface. An economical and effective method of decontaminating infected seed lots would have immediate application.
- Ascertain the efficacy of removal of alternate hosts from the field on disease severity in the field.
- Identify genotypes that support less secondary conidiation and thereby reduce secondary spread of the pathogen. Most sorghum genotypes seem to permit secondary conidiation on honeydew but Mantle (personal communication) has found some sweet sorghum genotypes with high sugar content that reduce secondary conidiation.
- Identify resistant sources possibly with novel mechanism of physiological resistance. Expand research to identify and develop male-sterile lines with ergot resistance.
- Develop productive hybrids and their seed parents with the following characteristics:
  - restorers with the ability to release abundant fertile pollen at low temperature and high humidity,
  - male-sterile lines that are tolerant to low temperature, i.e., with receptive stigmas that have the capacity to be rapidly fertilized with scant pollen at low temperature, and
  - the resultant F_1 hybrids combining the above-mentioned attributes of restorers and male-steriles.
- Determine the genetics of resistance of factors associated with ergot resistance and rapid fertilization (seed set) at low temperature.
- Explore the possibility of using gravity tables, air streams, and other methods for the removal of sclerotia from seed lots in seed-processing plants. Develop ways to rapidly clean seed processing equipment and to handle infected seed lots without contaminating healthy seed lots.
- Search for warm and dry periods during the year and/or areas to avoid ergot in hybrid seed production fields.

International collaboration

Until now, research on sorghum ergot has been carried out in Asia (India and Japan) and Africa (Botswana, Ethiopia, Nigeria, Rwanda, South Africa, and Zimbabwe). Research interest and expertise exist in South Africa, at the University of Zimbabwe, at the Imperial College (University of London, UK), and at ICRISAT Asia Center, Patancheru, India. The Imperial College has had significant strategic participation in sorghum ergot research in Zimbabwe. However, sorghum ergot research has been de-emphasized in some of these institutions during the last 4 years since it was not considered to be of a high priority.

Enhanced geographic distribution and the resurgence in importance of the disease in countries with near-total dependence on hybrid seed have escalated the demand for research on the disease. There is a need for renewed emphasis on sorghum ergot research with the participation of the public institutions and the seed industry in Australia, Brazil, and USA, and for active involvement of researchers with earlier experience in ergot-related work, A collaborative approach with distribution of responsibility is more likely to succeed than individual overlapping efforts, given the current scenario of constrained funding opportunities.

Quarantine procedures designed to prevent the introduction of pathogens are sometimes limited in their effectiveness, as observed with the recent outbreak of ergot in Australia. An excellent adjunct to quarantine procedures is collaborative research to control and study ergot with scientists and sorghum workers in those regions where the pathogen is already established. Such research will simultaneously reduce the risk of ergot introduction and provide controls that can be rapidly implemented if ergot is eventually introduced.

The three main areas of collaborative interest are fungicidal control, host-plant resistance, and ecology of ergot sclerotia. Fungicidal control will enable production of ergot-free seed, or at least with minimal numbers of ergot sclerotia. Knowledge about the contribution of sclerotia to ergot survival and spread, especially through seed, may be exploited to detect and either remove or destroy

ergot sclerotia in contaminated seed lots. These types of ergot control are hopefully needed only as interim procedures during attempts to identify host-plant resistance. The latter will be, at the very least, a time-consuming process to both confirm host-plant resistance to ergot, and then incorporate that resistance into agronomically useful germplasm adapted to regions where it is needed.

As sorghum workers collaborate to control ergot and produce ergot-free seed within and across geographical regions the risk of ergot spread to new regions will be reduced.

The development of highly effective fungicidal control in other regions would provide a control method that could be immediately employed in USA, or elsewhere, to reduce the impact of ergot when it is first observed. Fungicidal control may function in the short term for hybrid seed production but will be expensive, and may possibly be overwhelmed by high inoculum pressure and optimal conditions for ergot development. The loss of pollen viability in self-fertile sorghums under cool temperatures is also of concern in USA because much sorghum in the Northern Great Plains States of Kansas, Nebraska, and South Dakota flowers and matures during increasingly cooler temperatures. Fungicide application would not be an option in such fields. This is another indication of the importance of host-plant resistance that maintains resistance to ergot simply by producing viable pollen even in cool temperatures.

The identification of host-plant resistance requires a mobilization of global germplasm resources to assemble the best candidates for resistance screening. There needs to be a screening of all sources previously identified as having some level of ergot resistance, although there may be generally few (or no?) good sources of physiological resistance to ergot. Resistance to ergot could be greatly influenced by the environment, and it is imperative that sources be screened or that resistance be confirmed under multiple environments where ergot is present. In the absence of physiological resistance to ergot, additive factors that may be associated with reduced incidence and severity of ergot need to be identified. Such traits or resistance mechanisms in sorghum germplasm will then need to be incorporated singly or additively into sorghum A-lines or R-lines as appropriate. Because this is a time-consuming process, global cooperation and contribution are needed to address such global threats as ergot today.

Collaborative research on ergot at multiple global locations with a shared evaluation of methodology and germplasm across those locations should provide integrated controls for ergot that are best suited for each region. Perhaps, there is even the possibility of utilizing the ergot hyperparasite, *Cerebella,* as a biocontroi agent within an integrated control program for ergot. Continued communication of results through the International Sorghum and Millets Newsletter (ISMN), other publications, and through meetings and conferences will facilitate the dissemination of the most recent information and genetic resources. The current and future capability of communication through e-mail and the World Wide Web will vastly increase the global ability to communicate and exchange scientific information about ergot. The use of e-mail to globally exchange information on ergot has been phenomenally successful just within the past several months.

Acknowledgment

We would like to express our appreciation to Malcolm Ryley (Australia), C S Sangitrao (India), and Carlos Casela (Brazil) for providing us with pertinent information on some aspects of this review.

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Downy Mildew of Sorghum

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Introduction

Sorghum (*Sorghum bicolor* L. Moench.) is an important crop for human consumption and animal fodder in many areas of the world where semi-arid conditions prevail, including Africa, Asia, and the Americas. In 1994 sorghum was grown on 4.37 x 10^7 ha worldwide, which compares with 3.77 x 10^7 ha for pearl millet, the other major cereal grown in the semi-arid tropics (FAO Agrostat-PC, 1991-1996). The sorghum plant has good drought tolerance and produces a yield where other crops such as maize may succumb due to lack of moisture. Sorghum is also an ancient crop, having been cultivated for at least the last 5000 years. It was probably originally domesticated in northeastern Africa (Mann et al. 1983).

Sorghum suffers from many diseases, several of which have an adverse effect on yield. Investment in studying these pathogens can lead to disease control through well-informed disease management strategies. This in turn contributes to sustainable food production in epidemic-prone areas, particularly those that support a burgeoning population. Sorghum downy mildew, or SDM, (*Peronosclerospora sorghi* (Weston and Uppal (C G Shaw)) infects both sorghum and maize (*Zea mays* L.) and has caused serious economic yield losses in these crops. A major investment was made during the 1960's-1980's in an attempt to control this disease.

Twelve years ago Williams (1984) provided an excellent and comprehensive review of the different graminaceous downy mildews, including *P. sorghi.* This

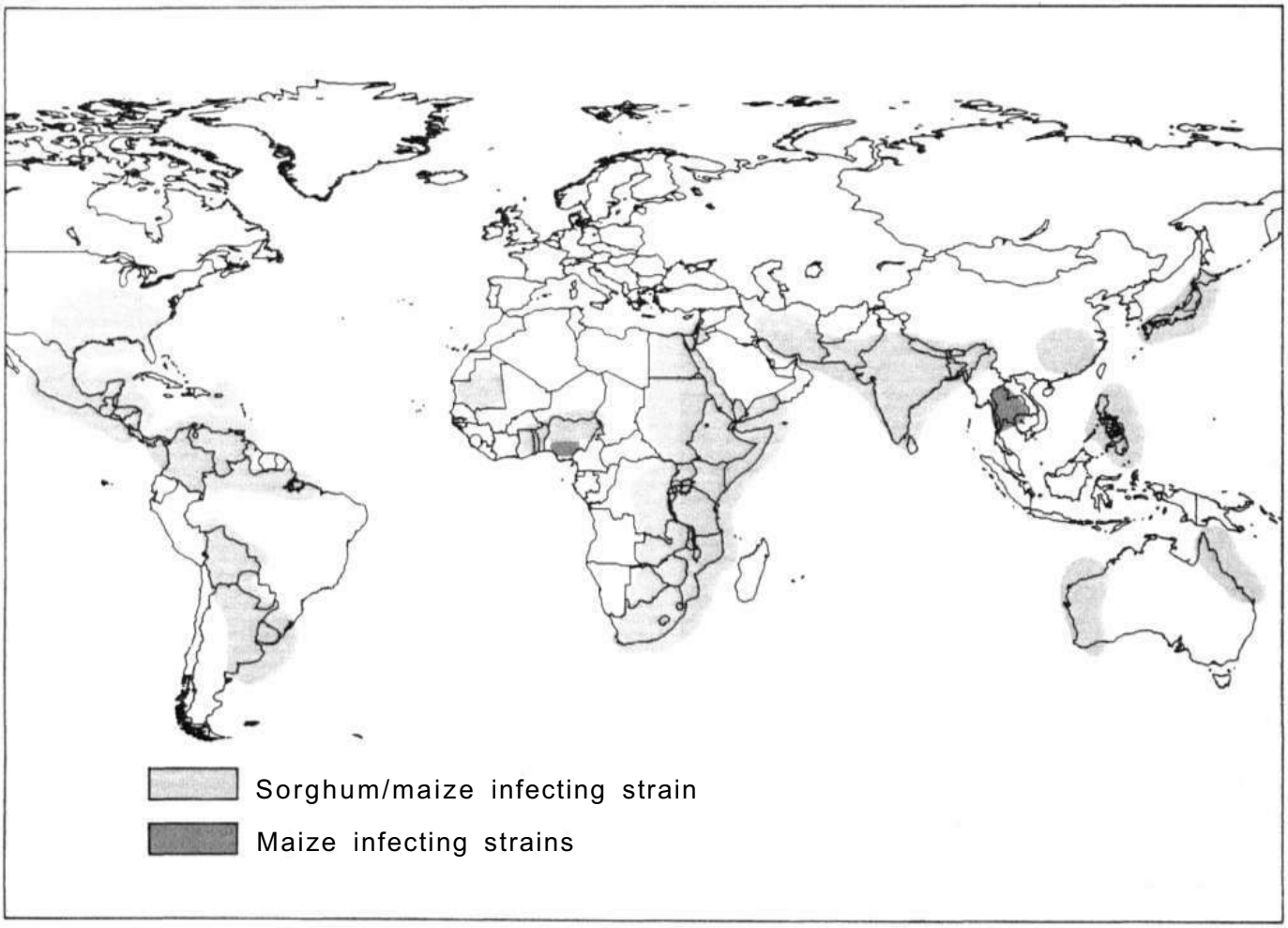

Figure I. Geographical distribution of *Peronosclerospora sorghi* showing regions where the sorghum/maize- and maize-infecting strains occur (the maize strain in Thailand has recently been designated specific rank as *P. zeae;* Yao 1991).

report presents our current state of knowledge of SDM with respect to sorghum, taking into account advances since the Williams review. Infection of maize or other hosts is only considered where deemed necessary, particularly if information is lacking on a particular aspect for sorghum.

Crop loss

Sorghum downy mildew is particularly destructive because systemic infection of the host generally results in a barren infloresence. The effect of infection on yield is best illustrated by reference to several reports in the literature. In a single season in the USA, a SDM epidemic in grain sorghum in the coastal counties of Texas caused an estimated loss of US$ 2.5 million (Frederiksen et al, 1969). Payak (1975) reported that in parts of India annual yield loss due to SDM was at least 10^5 t. In Venezuela, crop loss was so severe in the early 1970's that a national emergency was declared (Frederiksen and Renfro 1977). In Israel both forage sorghum and maize were severely infected with incidences of up to 50% (Kenneth 1976), and in the USA incidences of 90% have been reported (Frederiksen et al. 1969). The effect of systemic SDM is now more clearly understood, since models have been developed that show a linear relationship between incidence of systemic SDM and yield loss at normal sowing densities (Craig et al. 1989; Frederiksen et al. 1973; Tuleen and Frederiksen 1981).

Taxonomic history

A downy mildew infecting sorghum was first mentioned in India by Butler (1907), who considered it to be *Sclerospora graminicola.* Subsequently, Kulkarni (1913) observed the asexual phase germinated directly by means of a germ tube from conidia (rather than through zoospores from sporangia), and primarily on this basis he recommended designating it varietal rank - *S. graminicola* var. *Andropogonis-sorghi.* Further investigation of morphology and host range established the downy mildew infecting sorghum as *S. sorghi* (Weston and Uppal 1932). The differences observed in the mode of germination was deemed sufficient to eventually designate the new genus *Peronosclerospora* to house those graminaceous downy mildews, including *P. sorghi,* that produced conidia (Shaw 1976, 1978, and 1980). The genus *Sclerospora* was retained for species that germinated by means of zoospores from sporangia.

Origins and geographic distribution

The geographic distribution of SDM is illustrated in Figure 1. The pathogen has been reported to infect sorghum, maize, or wild hosts in at least 43 countries (Table 1). It is thought to be an 'Old World' disease, originating in Africa or Asia (Shaw 1981; Williams 1984) and subsequently spreading to theAmericas in the 1950's, where it was probably introduced (Frederiksen 1980a; Toler et al. 1959).

Causal organism

The following description of *P. sorghi* is based on that of Weston and Uppal (1932). The fungus produces asexual conidia (Fig. 2) and sexually produced oospores (Fig. 3). The conidia are produced on the leaf surface on erect conidiophores which grow out through stomata. The conidiophore comprises a basal cell and a more or less complex, usually dichotomously branched, expanded top (Figure 4). The basal cell is knobbed or bulbous at the bottom, then of fairly uniform diameter (7-9 µm) for a length of approximately 100-150 µm. It is usually delimited from the main axis by a complete septum. The main axis has a diameter of 15-20 µm, and is usually 80-150 µm long from the septum to the beginning of the branch system. The conidiophore branches by a succession of short, stout dichotomies involving primary, secondary, and tertiary branches. These terminate in tapering sterigmata approximately 13 µm long. The branches are arranged so the conidia borne on the sterigmata lie in a hemispherical plane. Conidia are suborbicular (15.0-28.9 µm x 15.0-26.9 µm, most frequently 21.0-24.9 µm x 19.0-22.9 µm), hyaline, with a thin wall and germinate directly by a hyphal germ tube.

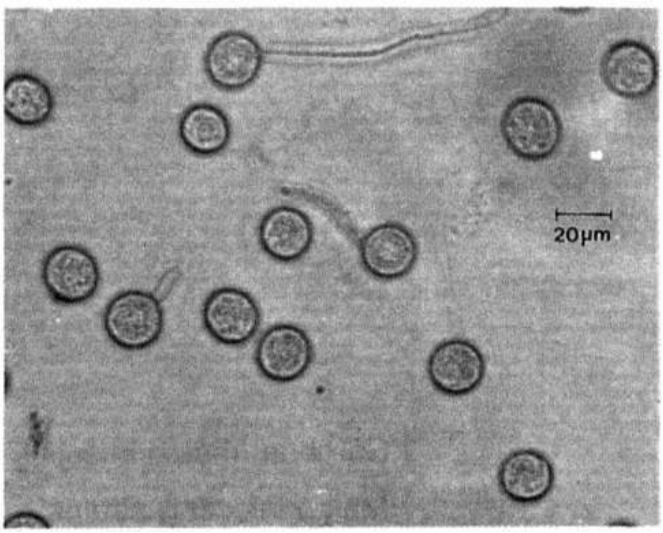

Figure 2. The asexual phase of *Peronosclerospora sorghi.* Conidia are sub-orbicular, hyaline and thin-walled. Some conidia are in the process of germinating by a single, unbranched hyphal germ tube.

Oospores are produced within the leaf mesophyll between the fibro-vascular bundles (Fig. 5). They are spherical, the majority being 31.0-36.9 µm in diameter, extremes range from 25.0-42.9 µm. The wall color is a light shade of Mars Yellow, and is 1.1-2.7 µm thick (extremes range from 0.3-4.3 µm). The oospore contains finely granular material with masses of oil globules. The oospore germinates by means of an unseptate, usually branched, hyaline germ tube, averaging 4.4 µm in width, extremes ranging from 2.5-8.3 µm.

Table 1. Countries from which *Peronosclerospora sorghi* has been reported[1].

Region or continent	Country
Africa	Benin, Botswana, Burundi, Egypt, Ethiopia, Ghana, Kenya, Malawi, Mozambique, Mauritania (Frison and Sadio, 1987), Nigeria, Rwanda, Somalia, South Africa, Sudan, Swaziland, Tanzania, Uganda, Zimbabwe, Zambia (de Milliano 1992)
Asia[2]	Bangladesh, China, India, Japan, Pakistan, Philippines
Australia	Queensland, Western Australia
North America	Mexico, USA (Alabama, Arkansas, Georgia, Illinois, Indiana, Kansas, Kentucky, Louisiana, Minnesota, Montana, Nebraska, New Mexico, Oklahoma, Tennessee, Texas)
Central America and the West Indies	El Salvador, Guatemala, Honduras, Panama, Puerto Rico
South America	Argentina, Bolivia, Brazil, Colombia (Burtica et al. 1992), Uruguay, Venezuela
Middle East	Israel, Iran, Yemen

1. Unless otherwise indicated, all reports were obtained from the Commonwealth Mycological Institute Distribution Maps of Plant Disease, Map no. 179, Edition 5, Issued 1 Apr 1988.
2. Previously a maize-infecting strain of P. *sorghi* was thought to occur in Thailand (Bonman et al. 1983). This race is now considered a separate species, *P. zeae* (Yao 1991).

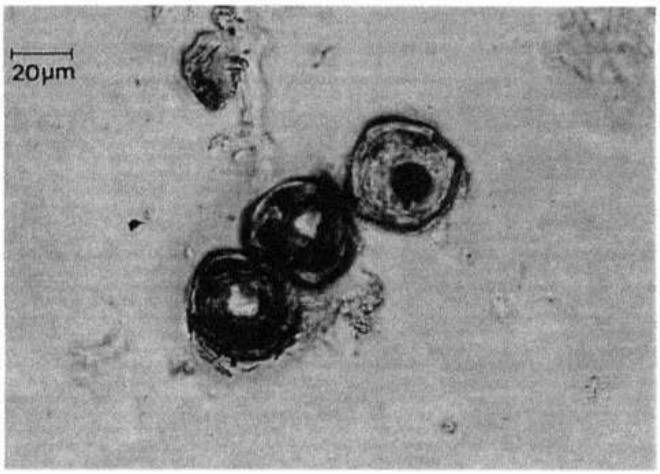

Figure 3. The sexual phase of *Peronosclerospora sorghi*. Oospores are spherical and thick-walled.

Peronosclerospora sorghi is an obligate parasite. Recently, however, *P. sorghi* has been successfullygrown in dual culture with host tissue on a modified White's medium (Kaveriappa et al. 1980). Bhat and Gowda (1985) later described an improved method for obtaining contaminant free dual cultures, but the inherent problems of maintaining these cultures has prevented them being widely used and most culture maintenance depends on inoculating seedlings of the host with conidia or oospores and using infected plants as a source of inoculum.

Disease symptoms

These are well described (Frederiksen et al. 1973; Williams 1984). Two types of symptoms can develop as a

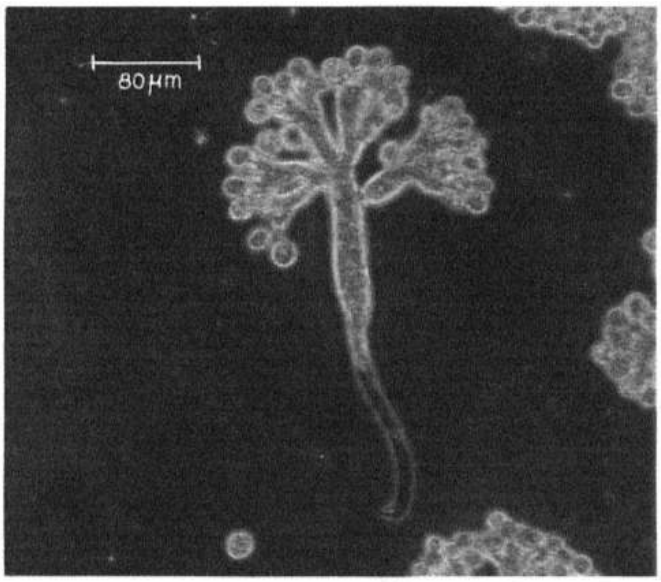

Figure 4. A mature conidiophore of *Peronosclerospora sorghi* showing the basal cell, the main body of the conidiophore and the conidia attached to the sterigmata.

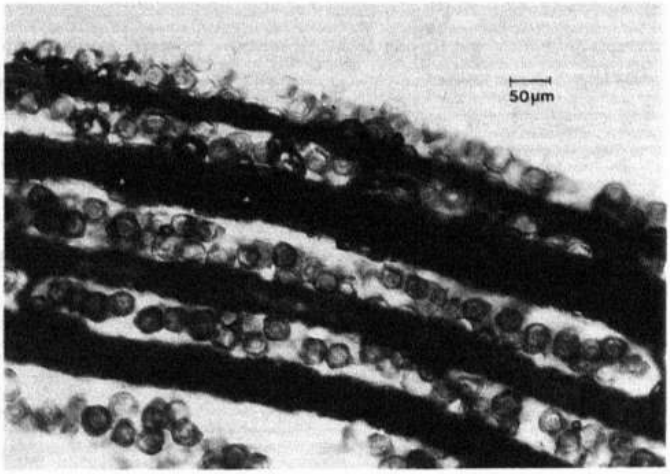

Figure 5. Oospores of *Peronosclerospora sorghi* are typically produced in parallel bands between the hbro-vaseular strands of the leaf.

Figure 6. A sorghum plant showing typical symptoms of systemic sorghum downy mildew infection. The leaves exhibit chlorosis with some pale streaking in the younger leaves; the leaves tend to be narrow, and the plant has an upright habit.

result of infection, either systemic symptoms (Fig. 6) resulting from an early infection and colonization of the growing point, or local lesions (Fig. 7) resulting from localized infection of the leaf lamina by conidia.

Systemic infection

Systemic infection resulting from infection by conidia or oospores can manifest itself at any stage from about one week after emergence. The symptoms are first seen as chlorotic areas emanating from the leaf base of the first leaves showing the infection. This chlorosis often covers half the lamina (called the 'half-leaf' symptom, Figure 8). Progressively greater proportions of the lamina of younger leaves show this symptom until the whole lamina is chlorotic. As the plant ages, white or pale yellow streaks develop from the base of the younger leaves (Fig. 9), which turn reddish brown as the inter-veinal tissue dies and the oospores develop. As the streaks turn brown they start to shred into long strips along the fibro vascular

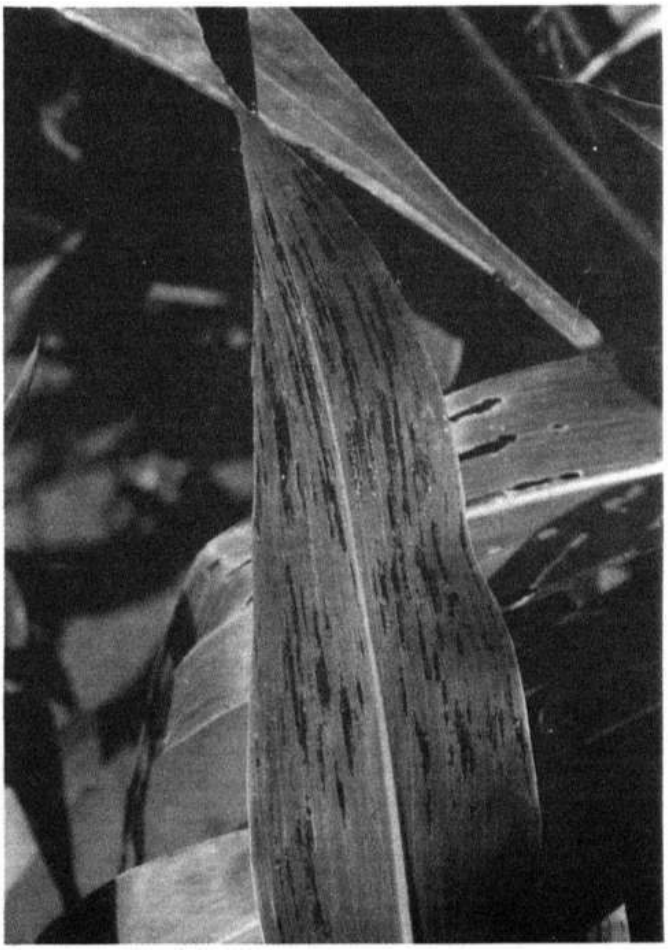

Figure 7. Typical symptoms of local lesions on sorghum caused by infection with conidia of *Peronosclerospora sorghi.* The local lesions can be seen as discrete chlorotic to purple-tan areas on the leaf lamina.

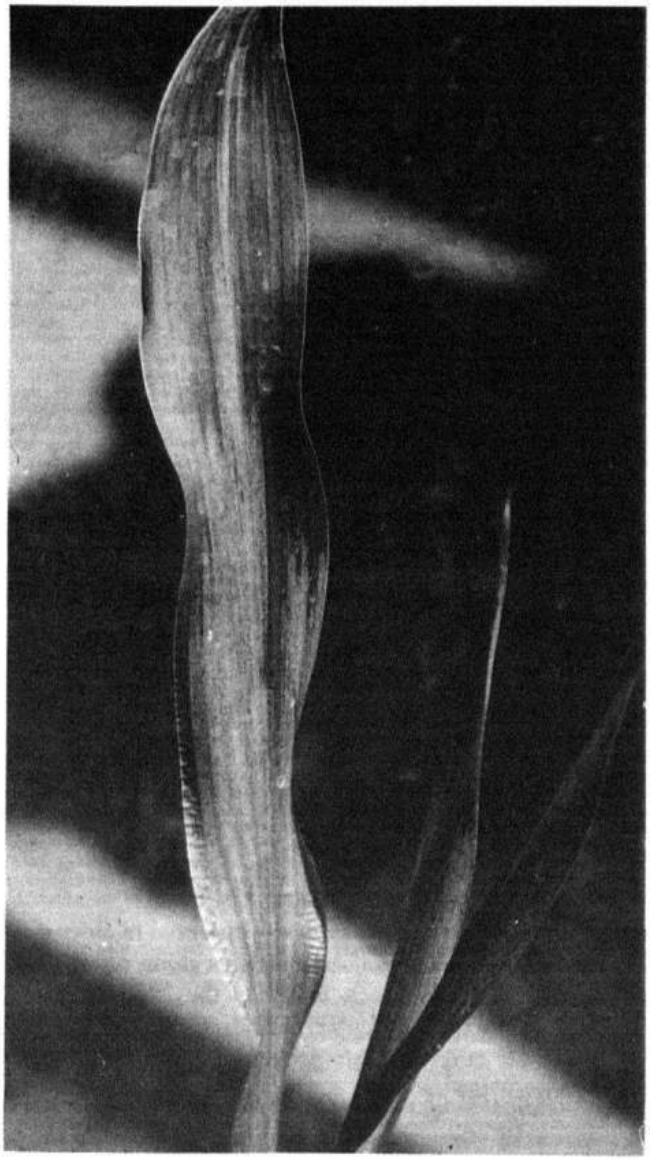

Figure 8. The typical 'half-leaf' symptom first manifested in a sorghum plant systemically infected with sorghum downy mildew. The lower part of the leaf is infected and chlorotic, while the upper portion remains green and non-infected.

strands of the leaf resulting in the symptoms of 'leaf-shredding' (Fig. 10). Plants that are systemically infected as seedlings can remain stunted and often die. Systemically infected plants are upright in habit, with narrowing of the foliage, and are generally barren, although some grain might be produced. Occasionally, a plant can recover and produce normal panicles with healthy, viable grain (symptom remission), but the basis for this phenomenon is unknown (Singh and de Milliano, 1989a and b).

Local lesions

Local lesions of SDM can occur on any leaf of a sorghum plant. Such lesions develop as discreet chlorotic to purple-tan areas, variable in size, but generally elongate with parallel edges (1-4 mm x 5-15 mm). In cool, humid weather conidia are produced on the leaves of sytemically infected plants and on local lesions during the night, particularly on the abaxial surface. This gives infected parts of the plant a white down-like appearance (Fig. 11).

Epidemiology and biology

The life cycle of P. *sorghi* is shown in Figure 12. Conidia of P. *sorghi* are produced in large numbers, they are thin-walled, ephemeral, and can cause the rapid build up of an epidemic. Oospores are tough walled, long-lived, and provide a perennating stage for the pathogen, as well as a mechanism for long-distance transport.

Conidia production, dispersal, and infection

Peronosclerospora sorghi has exacting environmental requirements for asexual reproduction and infection

Figure 9. The downy appearance of leaves infected with sorghum downy mildew resulting from the asexual sporulation of *Peronosclerospora sorghi.*

(Bonde 1982), Prior to conidiation in the dark, the host must be subject to a minimum period of 4 h of high light intensity (Schmitt and Freytag 1974). In maize, conidiophores form from within stomata under suitable environmental conditions over a period of about 6 h (Lal 1981). High relative humidity (RH) is crucial. Shetty and Safeeulla (1981a) found that systemieally infected sorghum leaves held in the dark at 20°C produced a maximum of 10,800 conidia cm^{-2} at 100% RH, but only 3,600 conidia cm^{-2} at 85% RH. None were produced at 80% RH. The optimum temperature for sporulation of an American isolate on maize was between 15°C and 23°C (Bonde et al. 1985). The optimum temperature for germination was 15°C and for germ tube growth was 22°C. However, germination was good at 10-19°C and germ tube growth rapid at 14-22°C. A dew period temperature of 10-33°C is required for 4 h for infection (Bonde et al. 1978). Conidial production in the field has a marked periodicity of release, and has a close relationship with temperature and moisture. Conidia are produced between midnight and 0500 h when temperatures are about 20°C and the RH > 85% (Shenoi and Ramalingham 1979). Conidia of SDM can be dispersed in air currents as far as 80 m (Rajasab et al. 1979). Germination occurs when conidia arc mature. The germ tubes grow at random over the leaf surface until encountering a stomata, when an appressorium forms over the stomatal opening (Jones 1971). The penetrating structure enlarges to form an oval shaped sub-stomatal vesicle, which gives rise to one or more infection hyphae. In susceptible cultivars, systemic colonization progresses by the development of haustoria that have up to eight finger-like tubes. Hyphal growth proceeds through the intercellular spaces of the mesophyll cells (Mauch-Mani et al. 1989). If a systemic infection develops, hyphae proceed to the apical meristem of

Figure 10. The typical pale, chlorotic streaking in the younger leaves of a sorghum plant systemieally infected with sorghum downy mildew. This symptom is indicative of the early stages of oospore production.

Figure 11. 'Leaf-shredding' typically observed in older sorghum plants systemieally infected with sorghum downy mildew. As the oospores reach maturity the leaves start to shred along the fibro-vascular strands, releasing the oospores into air currents; this probably allows them to be dispersed from the host.

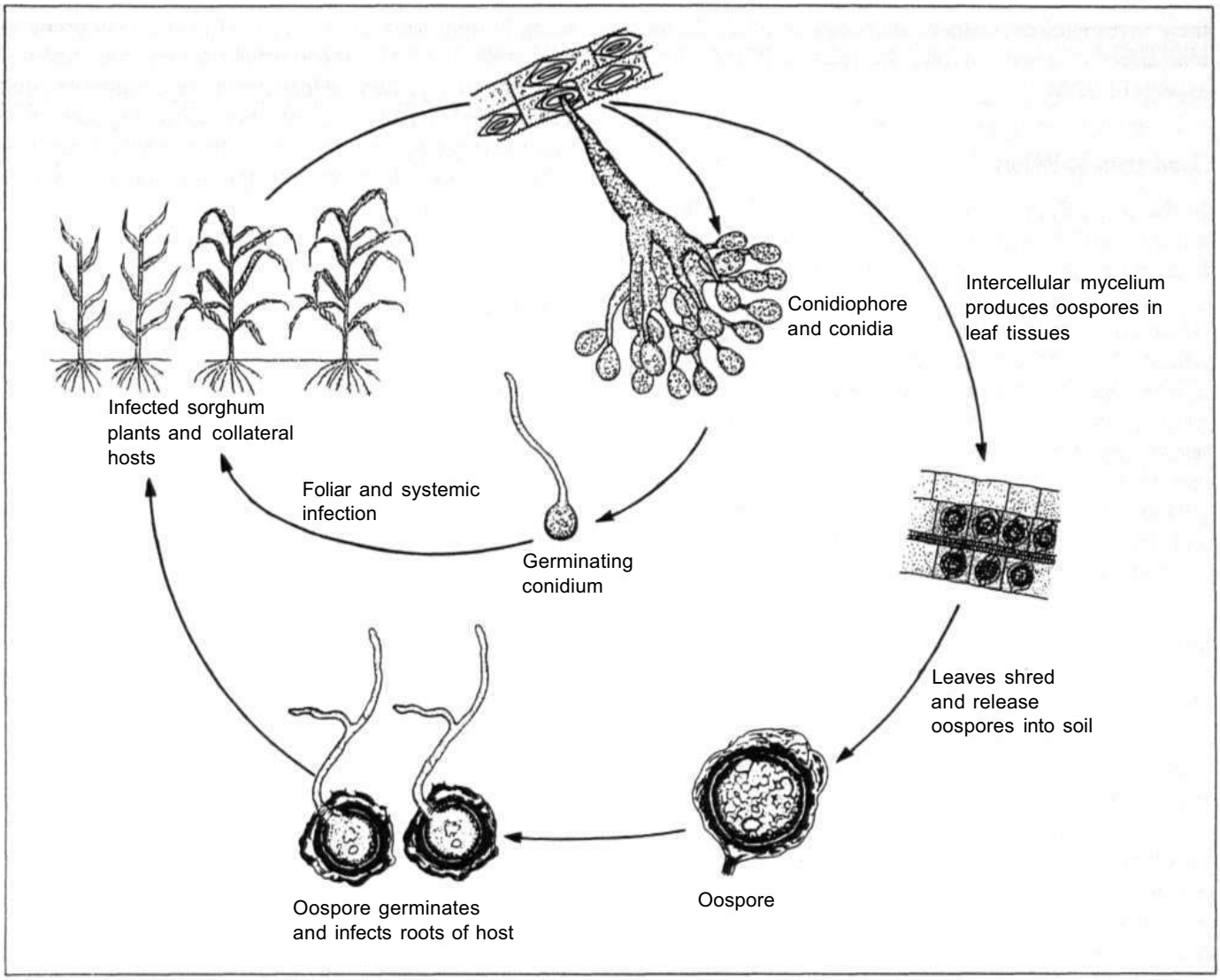

Figure 12. The disease cycle of *Peronosclerospora sorghi.* Whereas sexually produced oospores will generally provide only one cycle of infection per season, the asexually produced conidia from an infected plant can infect fresh hosts within the same season allowing rapid build up of an epidemic of sorghum downy mildew.

the plant and invade the developing leaves and flowering parts; the symptoms being manifest after at least 7 days. Plants are most vulnerable to systemic infection caused by conidia for approximately 20 days after emergence, after which time only local lesions are produced (Jones 1978; Shetty and Safeeulla 1981b). Local lesions develop approximately 7 days after infection (Cohen and Sherman 1977). In resistant cultivars necrosis occurs at the penetration site (Mauch-Mani et al. 1989).

Oospore production, dispersal, and infection

Oospores of SDM develop subsequent to the fusion of oogonia and antheridia initials in the mesophyll of sorghum leaves (Safeeulla and Thirumalachar 1955). Oospores can be dispersed by man or animals in soil adhering to feet or implements (Williams 1984). They can survive passage through the digestive tract of a cow and thus dispersal in manure is implicated (Safeeulla 1976). Seed transmission of oospores can also occur (Bain and Alford, 1969). They can also be dispersed by wind (Bock et al. 1995), and by water (Rajasab et al. 1979). Oospores can survive adverse conditions for several years (Safeeulla 1976). In soils the greatest incidence of infection was observed when the temperature was 25°C and the soil moisture potential 0.2 bar (Schuh et al. 1987). Soils with a high sand content support greater infection (Pratt and Janke 1978; Schuh et al. 1987). Host and nonhost roots can stimulate germination of oospores (Pratt 1978), the germ tube growing towards the meristematic region of the root where it forms an appressorium and infection peg (Safeeulla, 1976). Despite

these investigations, oospore germination and the factors that affect it remain among the least well understood aspects of SDM.

Seed transmission

In the USA, Bain and Alford (1969) illustrated external transmission of oospores with sorghum seed. Studies in India have indicated that *P. sorghi* could be transmitted internally in sorghum and maize seed either as mycelium (Kaveriappa and Safeeulla 1978) or as oospores (Upadhyay 1987). Mycelium was reported in both reproductive structures and in the endosperm of sorghum seed from systemically infected plants and a direct correlation was observed between seed transmission and embryo infection (Prabhu et al. 1983; Upadhyay 1987). Frederiksen (1980b) discussed ways in which oospore contamination and internal mycelial transmission of SDM can be avoided. Seed drying to below 20% moisture content, using healthy seed, producing seed in areas not prone to epidemics of SDM, breeding resistant hybrids, and observing strict quarantine legislation are all practises that can be used to avoid seed infection. Checking seed samples using molecular probes and DNA hybridization can also be used to check for seed transmission, of *P. sorghi* (Yao et al. 1990).

Collateral hosts

Collateral hosts, common in many areas where sorghum and maize crops are grown, are known to act as reservoirs for infection (Malaguti 1977). They can act either as a source of conidia early in the season or as a source of oospores that can infest the soil. Several species of graminae from the tribes Andropogonac, Maydae, and Panicae are reported to be susceptible to *P. sorghi* and are potential collateral hosts (Table 2).

Table 2. Host range of *Peronosclerospora sorghi*

Host	Author
Panicwn trypheron Shult.	McRae(1934)
Pennisetum americanum (L.) Leeke	Castellani(1939)
Para-sorghum sp.	Karunakar et al. (1994)
Sorghastrum rigidifolium Stapf.	Karunakar et al. (1994)
Sorghum aethiopicum (Hack.) Stapf.	Karunakar et al. (1994)
Sorghum x *almum* Perodi.	Tarr(1962)
S. arundinacium (Willd.) Stap.	Karunakar et al. (1994)
S. bicolor x *S. sudanense* (Piper) Stapf.	Futrell and Bain (1967)
S. bicolor (L.) Moench.	Bonde and Freytag (1979)
S. controversum (Steud.) Snowden	Karunakar et al., 1994
S. drummondii (Steud.) Millsp. & Chase.	Karunakar et al. (1994)
S. halepense (L.) Pers.	Frederiksen et al. (1965)
S. hewisonii (Piper) Longley	Bonde and Freytag (1979)
S. lanceolatum Stapf.	Bonde and Freytag (1979)
S. miliaceum (Roxb.) Snowden	Karunakar et al. (1994)
5. *niloticum* (Stapf. ex Piper) Snowden	Bonde and Freytag (1979)
S. plumosum (R. Br.) Beauv.	Nagarajan et al. (1970)
S. propinquum (Kunth.) Hitch.	Bonde and Freytag, (1979)
S. pugionifolium Snowden	Bonde and Freytag (1979)
S. purpurea-serecium (A. Rich.) Aschers. & Schwcrf.	Karunakar et al., 1994
S. sudanense (Piper) Stapf.	Nagarajan et al. (1970)
S. verticilliflorum (Steud.) Stapf.	Tarr(1962)
S. controversion (Steud.) Snowden	Bonde and Freytag (1979)
S. usamberance Snowden	Karunakar et al. (1994)
S. versicolor Anderss.	Bonde and Freytag (1979)
S. virgatum (Hack.) Stapf.	Nagarajan, et al. (1970)
Zea mais ssp. *mexicana* (L.) (Schrad.) litis.	Uppal and Desai (1932)
Zea mais (L.)	Bonde and Freytag (1979)

Table 3. Identification of pathotypes I, II, and III of *Peronosclerospora sorghi* in the USA by the differential reaction of four sorghum inbred lines[1].

Sorghum variety	Reaction to infection with pathotype I[2]	Reaction to infection with pathotype II	Reaction to infection with pathotype III
Tx412	S	S	S
Tx430	R	R	S
CS 3541	R	S	S
QL 3	R	R	R

1. Source; Craig and Frederiksen, 1983.
2. S = susceptible to infection, R - resistant to infection.

Seasonal disease development

An understanding of the factors that contribute to disease initiation and epidemic development is necessary if appropriate control methods are to be recommended. Studies of infection of sorghum and maize crops in several geographic regions indicate that oospores and conidia vary in importance as causal agents of infection. In parts of India where weather conditions are conducive to asexual spore production conidia are responsible for most of the infections, and early sowings can escape disease (Rajasab et al. 1980; Ramalingham and Rajasab, 1981). In other areas, including the USA, oospores are the major source of infection (Schuh et al. 1987). Soil temperature, moisture, and texture are likely to influence the incidence of systemic infection in these regions. In South America collateral hosts are thought to be an important source of disease each season (Malaguti, 1977). Although it has not been applied to downy mildew of sorghum, Drepper et al. (1993) illustrated the potential use of modeling epidemics to identify conditions conducive to epidemic development of the maize downy mildew in Thailand. This could provide a useful tool for understanding the conditions that support epidemics of SDM at different locations.

Variability within *Peronosclerospora sorghi*

Morphological variability between isolates of *P. sorghi* is limited (Bock 1995). Adaptation to specific environmental conditions is not apparent either. There appears to be little variability in environmental requirements between isolates from diverse locations (Bock 1995; Bonde et al. 1985).

Variability is thought to occur at the host range level. As a result, *P. sorghi* has been subdivided into'sorghum/maize' and 'maize' infecting strains. However, as more information has become available on the affiliations of the maize strains, most have eventually been designated as separate species. For example, *P. heteropogonii* was designated specific rank after studies of a maize strain of *P. sorghi* showed it to be ,n a different species (Siradhana et al. 1980). Similarly, recent studies suggest that a maize strain of *P. sorghi* from Thailand should be given specific rank as *P. zeae* (Bonde et al. 1992; Yao 1991). Molecular and biochemical tools have proven useful for investigating the variability of these species (Bonde et al. 1984, Micales et al. 1988, Yao 1991). Further observations indicate that at least one other maize strain of *P. sorghi* occurs in Africa (Anaso ct al. 1987; Fajemisin 1980). Further work is needed to confirm its identity.

The first indication of pathogenic variability of P. *sorghi* on sorghum was observed in the USA in the late 1970's when a previously resistant and popular sorghum hybrid was observed to be infected with SDM (Craig and Frederiksen 1980). Subsequently three distinct pathotypes were identified on sorghum in the USA from the differential reaction of the inbred lines Tx412, Tx430, CS 3541, and QL 3 (Table 3, Craig and Frederiksen 1983). Other pathotypes have also been identified in Brazil (Fernandes and Schaffert 1983), Honduras (Craig and Odvody 1992), and Zimbabwe where there are reports of the resistant variety QL 3 being susceptible (de Milliano and Veld, 1990). Pawar et al. (1985) tested 75 sorghum varieties for their reaction to 16 isolates from different geographic regions. They found that differential reactions identified each of the isolates as a different pathotype. Those from Africa (Nigeria and Ethiopia) and Asia had greater virulence than those from the Americas.

Control

Chemical control

Prior to the late 1970's several different fungicides had been used in an attempt to control the graminaceous downy mildews (Balasubramanian 1975; Singh et al. 1970). None of these had proved effective. However, in the late 1970's the discovery of the acyl-alanine fungicide

metalaxyl-([N-(2-methoxyacetyl)-N-(2,6-xylyl)-DL-alaninate) revolutionized the chemical control of these pathogens (Schwinn 1980). In India, seed treatments of 1 g a i kg^{-1} of seed plus a foliar spray of 1 g a i L^{-1} 40 days after emergence (DAE) or foliar sprays of 2 g a i $litre^{-1}$ at 10 plus 40, or 20 plus 50 DAE gave complete control of systemic SDM (Anahosur and Patil, 1980, Venugopal and Safeeulla, 1978). Seed treatment alone did not fully protect the plant or nodal tillers from systemic infection, and a spray regime was required to prevent a low incidence of late systemic infection developing and to control local lesions. However, in most cases it is unlikely that the additional spray treatments are economic. Other studies in the USA, where oospores constitute the bulk of systemic infection, indicated concentrations of metalaxyl as low as 0.05 g a i kg^{-1} seed gave complete control, and concentrations greater than 1 g a i kg^{-1} seed caused seedling death (Odvody and Frederiksen, 1984).

It remains a possibility that the graminaceous downy mildews may develop resistance to metalaxyl, a view that is supported by the fact that other oomycetes have developed resistance to this fungicide (Bruck et al. 1982; Georgopoulos and Grigoriu 1981). Judicious use of metalaxy as a seed treatment is recommended, perhaps in conjunction with other means of disease control. Apart from the use of metalaxyl, soil sterilization has also been shown to be effective in reducing infection through soilborne oospores, but may not be practical or economic (Matocha et al. 1974).

Cultural control

Crop rotation. Roots of host and non-host plants cause germination of oospores (Pratt 1978) and 'bait crops' (e.g. *Linum usitatissimum)* grown in infested soil can reduce the incidence of infection in susceptible sorghum crops sown in the same soil (Tuleen et al. 1980). This will have greatest effect where oospores are the principal source of systemic infection and infestation of the soils is severe.

Deep tillage. Deep tillage effectively reduced both the incidence of SDM and the oospore content in the upper strata of infested soil (Tuleen et al. 1980; Janke et al. 1983). However, it is an expensive operation and probably not a cost-effective means of control.

Over-sowing and roguing of diseased plants. By sowing up to 50% more than the recommended agronomic optimum, the stand loss due to moderate disease incidence leads to an acceptable plant density of healthy plants at harvest (Frederiksen et al. 1973). A disease incidence of 20-30% can be borne at this level of oversowing before yield is reduced. Roguing results in a reduced oospore population, and consequently the incidence of systemic infection in subsequent crops is reduced (Janke et al. 1983). It also reduces the source of within- season asexual spores. Roguing can also be usefully applied to weed hosts so as to reduce the sources of external inoculum (Malaguti 1977).

Sowing date. In Dharwad, India, late sowings of sorghum had an increased incidence of SDM (Balasubramanian 1974). Similarly in Israel, early sowings of sweet corn avoided the disease (Cohen and Sherman 1977). This is because conidia produced in large quantities from plants that were infected early provided an increased inoculum pressure, resulting in a higher disease incidence on late-sown crops. However, where conidia are not the major source of inoculum late sowings might not have a higher disease incidence. Tuleen et al. (1980) found a lower incidence of systemic SDM in late sowings in the USA, where oospores were the principal source of infection.

The effect of host-plant nutrition. There is no clear effect of nutrition on the incidence of systemic SDM. Balasubramanian (1973) found that phosphorus added to the soil increased the incidence of SDM on sorghum plants, but nitrogen levels had no effect. Gupta and Siradhana (1978) observed that the absence of phosphorous, and deficiency of nitrogen reduced incidence of systemic infection, but potassium deficiency caused greater incidence of SDM on maize grown in a nutrient solution,

Bonman and Pittipornchai (1984) found that in early-sown maize crops in Thailand the incidence of maize downy mildew was lowered by the application of nitrogen or nitrogen plus phosphorus, but late-sown crops had a high incidence regardless of treatment. It is likely that the effect of nutrition is associated with plant age, inoculum type and pressure, and other environmental variables.

Biological control

A chytrid fungus (*Gaertennomyces* sp.) was found to effectively parasitize oospores (Kunene et al. 1990). It can reduce the incidence of infection in treated soils by up to 58%. However, field application of this organism has not been developed and it is unlikely that bio-control of SDM will become a practical reality in the near future. Other parasites of oospores have also been observed although they have not been studied in detail (de Diaz and Polanco 1984, Lakshmanan et al. 1990a).

Host-plant resistance

There are many reports in the literature of screening sorghum lines for resistance to SDM. (Anahosur et al. 1984; de Milliano et al. 1990; Frederiksen et al. 1973; Henzell et al. 1982; Kumar et al. 1979; Lakshrnananet al. 1990b; Lu et al. 1990; Sarwar and Rao 1979; Shivana and

Anahosur 1988; Shivana and Anahosur 1990; Williams et al. 1982). In India, the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) has screened a great deal of germplasm. Up to 1988, a total of 13,101 accessions from 73 countries had been screened in the field for resistance to *P. sorghi.* Of these 46 accessions were resistant to *P. sorghi* (Y D Narayana, personal communication). These accessions were from geographically diverse sources (Table 4). Many lines of germplasm have also been screened in the USA (Frederiksen et al. 1993).

Table 4. Origin and number of accessions of the world collection of sorghum germplasm screened in the field by ICRISAT from 1981-88 and found to be resistant to sorghum downy mildew at Dharwad, Karnataka, India.

Origin[1]	Number of countries	Number of lines screened	Number of lines resistant
Eastern Africa	7	3345	18
Western Africa	14	3324	4
Southern Africa	9	930	2
Northern Africa and the Middle East	8	252	0
Indian subcontinent	5	3403	12
Southeast Asia and the Far East	8	218	0
North and Central America	7	1476	4
South America	3	19	0
Europe	9	71	0
Eastern Europe	-	40	0
Australia and Oceania	2	23	6
Total	73	13101	46

1. Eastern Africa: Ethiopia, Kenya, Sudan, Somalia, Tanzania, Uganda, Zaire.
Western Africa: Benin, Burkina Faso, Cameroon, Congo, Central African Republic, Chad, Ghana, Gambia, Cote d'Ivoire, Mali, Nigeria, Niger, Sierra Loene, Senegal.
Southern Africa: Angola, Botswana, Lesotho, Malawi, Malagasy Republic, South Africa, Swaziland, Zambia, Zimbabwe.
Northern Africa and the Middle East: Egypt, Israel, Iran, Iraq, Lebanon, Syria, Saudi Arabia, Yemen.
Indian subcontinent: Afganistan, Bangladesh, India, Nepal, Pakistan.
Southeast Asia and the Far East: Myanmar, China, Indonesia, Japan, Philippines, South Korea, Taiwan, Thailand.
North and Central America: Cuba, El Salvador, Gautamela, Mexico, Nicaragua, USA, West Indies.
South America: Argentina, Uraguay, Venzuela.
Europe: Belgium, Cyprus, France, Greece, Hungary, Italy, Portugal, Spain, Turkey.
Eastern Europe.
Australia and Oceania: Australia, Papau New Guniea.

Figure 13. The spreader row technique employed by breeders to ensure effective screening of sorghum germplasm against sorghum downy mildew. Note the older infeetor rows sown to the left and right of the four rows of test material. The infector rows were sown about 3 weeks prior to the test material.

In an attempt to screen sorghum cultivars and to identify stable resistance and differences in pathogen-virulence between locations the International SDM Nursery (ISDMN) was established in 1976 (Williams et al. 1980). Selected results of multilocational testing of resistant sorghum accessions at ISDMN test sites are shown in Table 5 (Dr Y D Narayana, personal communication). Although the results of the ISDMN did not initially indicate pathogen variability of *P. sorghi* on sorghum, the existence of pathotypes of *P. sorghi* was subsequently reported (Craig and Frederiksen 1983; Pawar et al. 1985). This indicates that durable, broad-based resistance to this pathogen should be sought.

Methods for screening for resistance. To identify resistance reliably and to investigate the inheritance and genetics of resistance it has been necessary to develop effective screening methods:

- Natural infection (Anahosur and Hegde 1979). This method is probably the least effective as there is no attempt to ensure the exposure of different test materials to the same amounts of inoculum.
- Spreader rows as a source of asexual inoculum (Fig. 13; Cardwell et al. 1993; Anahosur and Hegde 1979). The spreader rows are generally inoculated to ensure a uniform and high level of infection (Cardwell et al. 1993). The test material is sown approximately 3 weeks after the spreader rows. This allows the systemic infections in the spreader rows to develop and produce large quantities of asexual spores over the period when

Table 5. Sorghum downy mildew incidence in selected resistant accessions in the International Sorghum Downy Mildew Nursery during 1976-86.

		Highest disease incidence at locations (% plants infected)						
Entry	Origin	Mana[1]	Per	Jab	Sam	Dha	Mys	Tex
IS 1317	Tanzania	-[2]	0(1)[3]	-	-	3(5)	0(3)	0(1)
IS 2132	USA	-	0(1)	-	-	0(5)	3(3)	0(1)
IS 2204	India	-	0(1)	-	-	0(5)	6(5)	0(1)
IS 2473	USA	-	0(1)	-	-	3(5)	6(3)	0(1)
IS 2482	USA	-	0(1)	-	-	2(5)	6(5)	0(1)
IS 3443	Sudan	0(3)	3(4)	0(1)	0(1)	7(5)	6(6)	-
IS 3546	Sudan	-	0(1)	-	-	1(5)	6(3)	0(1)
IS 3547	Sudan	0(3)	0(4)	0(1)	0(2)	0(6)	0(3)	-
IS 4696	India	-	0(1)	-	-	0(5)	0(2)	0(1)
IS 5616	India	-	0(1)	-	-	4(5)	0(3)	0(1)
IS 5628	India	-	0(1)	-	-	5(5)	0(2)	0(1)
IS 5651	India	-	0(1)	-	-	4(5)	0(2)	0(1)
IS 5665	India	-	0(1)	-	-	0(5)	0(2)	0(1)
IS 5743	India	-	0(1)	-	-	0(5)	0(2)	0(1)
IS 7528	Nigeria	0(3)	0(4)	0(2)	0(2)	5(5)	14(3)	-
IS 8185	Uganda	0(3)	0(4)	0(2)	0(2)	3(6)	15(5)	-
IS 8283	Uganda	6(2)	0(2)	0(1)	0(1)	2(5)	3(5)	-
IS 8607	Uganda	3(3)	0(4)	0(2)	0(2)	5(6)	13(6)	-
IS 14387	Zimbabwe	-	0(1)	-	-	0(5)	2(2)	0(1)
IS 18757	Australia	0(4)	0(5)	0(2)	0(2)	0(11)	0(11)	-
IS 22227	Australia	0(4)	0(5)	0(1)	0(2)	0(7)	12(4)	-
IS 22228	Australia	0(4)	0(5)	0(1)	0(1)	4(7)	11(4)	-
IS 22229	Australia	0(4)	0(5)	0(1)	0(1)	0(7)	28(4)	-
IS 27042	India	0(2)	0(3)	-	0(1)	0(5)	7(5)	-
DMS 652 (Susceptible check)	India	100(4)	36(5)	9(2)	100(2)	100(5)	100(5)	45(1)

1. Locations: Manfredi and Pergamino (Argentina), Jabaticobal (Brazil), Samaru (Nigeria), Dharwad and Mysore (India), Texas (USA).
2. - not tested at that location.
3. Numbers in parentheses indicate number of years tested at each location.

the test materials are susceptible. Humidity can be increased by using sprinkler irrigation to provide ideal conditions for asexual spore production as Williams and Singh (1981) illustrated using pearl millet downy mildew. Anahosur and Hedge (1979) compared five different methods, and found that the infector row technique was the most effective at producing a high and uniform incidence of infection in susceptible test materials.

- Oospore infested plots as a source of sexual inoculum (Craig 1980). With this technique monocropping and plowing in of infected sorghum from test plots and spreader rows is used to increase the oospore content of the soil. Test material is then sown. The main source of infection is through the oospores in the soil.
- A combination of spreader rows and oospore-infested plots (de Milliano, personal communication). This technique is used by 1CRISAT to screen for resistance to SDM both at Dharwad, in India, and at Matopos, in Zimbabwe. As in the previous technique, infected sorghum is incorporated to increase the oospore content of the soil. Spreader rows are also sown to act as a source of conidial inoculum. The advantage of this system is that plants are subject to infection by both oospores and conidia, which have different sites of entry, and for which there may be evidence of differential resistance, at least in maize (Frederiksen et al. 1973).
- Artificially applied asexual inoculum (Schmitt and Freytag 1974; Craig 1976; Narayana et al. 1995). This

system is generally used in a controlled environment. Seedlings of test material are either whorl- or spray-inoculated with a suspension of mature conidia. The advantage of this system is that optimal conditions can be maintained and the amount of inoculum is regulated. It can also provide a rapid technique for screening large quantities of material in a short time. The ephemeral nature of conidia of *P. sorghi* means they must reach the host within a short time of maturation so as to ensure infection. Craig (1987) utilized the natural infection cycle of SDM to develop a system for producing and storing conidia, that could later be used to inoculate material. However, the most successful long-term storage technique was developed by Gale et al. (1975) and Long et al. (1978). Maize seedlings could be infected with conidia of various *Peronosclerospora* spp. after more than 2 years storage in 10% dimethyl sulphoxide held in liquid nitrogen.

- Tissue culture. Currently this method of screening for resistance to SDM does not have a practical application. Mauch Mani et al. (1989) found that callus cultures of resistant cultivars were not infected by conidia of P. *sorghi,* while those of susceptible cultivars were. However, Gowda and Bhat (1992) obtained a viable dual culture when they applied asexual inoculum to the callus of a SDM-resistant cultivar of sorghum, although a second resistant line remained uninfected by *P. sorghi* in culture. This system needs to be investigated in greater depth before it can be used as a tool in resistance breeding.

Assessment methods. For comparing host reactions it is necessary to develop an effective (both accurate and precise) assessment method. Scoring of systemic infection is straightforward. The incidence of systemically infected plants can be recorded on at least two occasions during the season; This should provide a realistic estimate of the incidence of systemic infection (Williams 1984). Assessment of local lesions requires that both incidence and severity data be recorded. In the past a 1-5 scale has been used to score this type of infection (Singburaudom and Williams 1978; Frederiksen 1980a). Shenoi and Ramalingham (1976) developed a 1-4 scale to assess the severity of local lesion infection.

Genetics and inheritance of resistance. Sorghum is a self-pollinated species which means genetic uniformity can be attained (Frederiksen et al. 1973). However, it can be induced to cross-pollinate. Studies of the inheritance of resistance in sorghum undertaken by various authors suggest that it is dominant to susceptibility (Rana et al. 1978; Sifuentes and Frederiksen 1988) although earlier-workers found dominance of susceptibility (Miller 1966; Puttarudrappa et al. 1972). Quantitative inheritance has also been observed by some authors. Puttarudappa et al. (1972) suggested that two complementary genes controlled resistance. Bhat et al. (1982) concluded that a primary dominant gene with either one or two duplicate genes and three complementary genes contributed to resistance. Nider et al. (1974) reported polygenic control. Craig and Schertz (1985) illustrated that the resistance to SDM expressed by the inbred line SC414-12 was conferred by a single dominant gene. This resulted in an incompatible host-pathogen interaction that inhibited pathogen development and sporulation on inoculated leaves. Gimenes-Fernandes et al. (1984) found that resistance was conferred by one or two dominant or partially dominant genes that were different. Neither author detected cytoplasmic factors of inheritance. Sifuentes and Frederiksen (1988) investigated the inheritance of resistance to three pathotypes of *P. sorghi.* Their results indicated that the resistant variety QL 3 has two dominant genes conditioning resistance to each of the three pathotypes. Reddy et al. (1992) also found resistance in QL 3 dominant to susceptibility: a two loci model with independent segregation and a combination of complementary and inhibitory inter-allelic interaction appeared to be the most appropriate in explaining the inheritance pattern they observed. Further investigations are needed to characterize the inheritance of resistance to SDM in other sorghum lines, and the mechanisms of resistance, which remain poorly understood. Resistance, preferably of a durable nature needs to continue to be incorporated into agronomically suitable varieties. Recently symptom remission has been observed in systemically infected plants. It might be that this is another resistance mechnism that could be utilized (Singh and de Milliano, 1989a and b).

Integrated control

Integrated control involves the use of two or more methods of control to bring about a reduction in the incidence of the disease (Odvody et al., 1983). The suitability of the methods used depends on the local conditions. Thus, a good knowledge is needed of the epidemiology of the disease and control options available to a farmer in a given area before an integrated package can be implemented. Integrated control can involve chemical control (for example, metalaxyl seed treatment), cultural control (for example, deep plowing or crop rotation) and the use of host-plant resistance. The combination of control methods can be mutually beneficial. For example, Odvody and Frederiksen (1984) suggest the use of a resistant variety and seed treatment could extend the life of the host resistance and prevent development of

fungicide resistance in the pathogen. The final methods chosen must depend on their effectiveness in a particular situation and the farmer's ability to use them.

In conclusion

A great deal of work has been done to increase our knowledge base of downy mildew of sorghum during the last 30 years. The availability of a number of different disease management strategies attests to the success of this investment. However, there are aspects of this pathogen that remain poorly understood. Further investigation may enhance our understanding and contribute to the continued control of SDM. The pathogen remains a threat to the production of sorghum (and maize) in Africa, Asia, and the Americas. The breakdown of resistance to SDM in the USA in the late 1970's suggests we should not be too complacent. However, host plant resistance probably offers the best solution to the control of SDM, as well as being the most environmentally sound method for the future management of this disease.

Acknowledgments

We appreciate the financial support of the Associate Professional Officers Scheme of the Overseas Development Administration, UK, for the first author. Dr Y D Narayana (ICRISAT) kindly provided information on the ICRISAT sorghum breeding program and Figures 8 and 14. Dr R Bandyopadhyay (ICRISAT) provided Figure 5.

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Genetics and Plant Breeding

Sorghum Line with Increased Frequency of Polyembryony

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Of nine sorghum genotypes screened for polyembryony in germinating seeds, cultivar Negritjanskoje 3366/2 (*S. nigricans* Rukz. and Snowd.) exhibited the highest frequency of polyembryony (0.12%). The proportion of plants with polyembryonic seeds in their panicles was 34.5%.

In 1992, polyembryony frequency (PF) was evaluated in 18 families derived from this cultivar (the offspring of one plant was considered as a family). Seeds from 7-10 plants from each family were pooled for analysis. In 6 of the 18 families studied, twin seedlings were found with a frequency of 0.11-0.31%. Two families, N-3 and N-9, had distinctly high PFs (0.31 and 0.29%), that were not significantly different from each other, but differed from the PFs of other families at $P \leq 0$ 0.05.

In the following generations (G_2-G_3), the offspring of individual plants from these families were studied. In G_2, the progeny of N-3 and N-9 families, N-3-6 and N-9-6, approximately 30% of the plants had 1-3 polyembryonic seeds in their panicles. In the family N-9-6, two plants were found to have PFs of 0.53 and 1.7% in germinating seeds. In the next generation this family also showed a higher PF than other families and lines. Neither haploids nor polyploids were found among twin seedlings in this material.

The twins varied in their morphological characters. At present, there is no research that establishes any link between twin morphology and cytogenetic features with its origin. Perhaps, the cases of anomalous disposition of embryos reflects the manifestation of apomixis (Tan et al. 1992, Marina 1994).

In the family N-9-6, some twins were found to have seedlings turned at an angle of 90° to each other. In these twins the weak seedling occupied the micropilar part, whereas the vigorous seedling emerged from the central part of the grain. This work suggests that the family N-9-6 is a line with increased frequency of polyembryony and apomixis and could be used in further studies.

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Nuclear-cytoplasmic Interactions in Restoration of Male Fertility on '9E' CMS-inducing Cytoplasm

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The restoration of male fertility in different CMS-inducing sorghum cytoplasms was found to be controlled by one or a few dominant genes that specifically interact with definite cytoplasmic genes (Schertz and Pring 1982, Tripathi et al. 1985). Lines with recessive genes at the same nuclear loci maintain male sterility. Nuclear genomes of these lines can be transferred into sterility-inducing cytoplasms by successive backcrosses, resulting in CMS lines. The reaction of desired CMS lines and the source line of CMS in list crosses with fertility restorers should be identical, because both of them possess the same cytoplasm and recessive nuclear genes (maintainers of CMS). However, we found that two isoplasmic CMS lines of sorghum can display a principally different reaction on the same tester line fertility restorer.

One of the lines in our experiments was ['9E'] Tx398 (Dr K F Schertz supplied the seed). By backcrossing this line with Milo 10 we have developed another CMS line: ['9E'] Milo 10. The tester fertility restorer was our line KVV 114.

The F, hybrid ['9E'] Tx398 x KVV 114 was fertile (Table 1). Segregation in the F_2 gave a 9:7 ratio (fertile and partially fertile versus partially sterile and sterile plants). This ratio indicates that restoration of male fertility in this hybrid combination is controlled by the interaction of two complementary dominant genes (MS_{9E1}, MS_{9E2}).

However, the F_1 hybrids ['9E'] Milo 10 x KVV 114 were predominantly sterile, with a few semi-sterile plants (Table 1). Similar patterns of segregation were also observed in the BC_1 generation obtained by crossing sterile plants from the F_1 with KVV 144.

These data demonstrate that two isoplasmic CMS lines of sorghum on the '9E' cytoplasm have different reactions with the same tester line. Although both CMS lines possess the same CMS inducing cytoplasm, the tester line is a restorer for one of them, and a maintainer for the other. This result can be explained by the action of one or several dominant inhibitor genes present in Milo 10 that suppress the action of the restorer gene of KVV 114. A dominant gene-inhibiting restoration of male fertility of the cytoplasm of *Triticum timopheevi* Zhuk has been described in wheat (*T. aestivum* L., cv. Chris) (Du and Maan 1992). However, this explanation seems less convincing, because fertile plants without gene-inhibitor(s) should appear in the BC_1 as a result of recombination during gametogenesis in the F_1 plants. Nevertheless, the amount of partially sterile and partially fertile plants did not increase in BC_1 in comparison with the F_1. One alternative explanation of this phenomenon, though quite speculative at this stage, may be that during backcrossing Milo 10 into the '9E' cytoplasm, the cytoplasmic genes that control the CMS phenotype changed. The influence of certain nuclear genotypes on the composition of the mitochondrial genome have been described in maize and in some other plants (Zabala et al. 1989). Both the above-stated hypotheses will be studied in future experiments.

Table 1. Fertility of hybrids of two genetically diverse CMS-lines with '9E' cytoplasm (Tx398 and Milo 10) in crosses with restorer line KVV 114.

Hybrid combination and generation	Number of fertile/sterile plants[1]			
	F	PF	PS	S
['9E'] Tx398 x KVV 114				
F_1	3	1		
F_2 obs.	22	9	8	12
exp.(9:7)	28.7		22.3	
		X^2 = 0.427 P<0.05		
['9E'] Milo 10 x KVV 114				
F_1	0	2	13	30
BC_1	0	2	6	14

1. S = sterile (0% seed set), PS = partially sterile (<25%), PF = partially fertile (25.75%), F = fertile (>75%).

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Germplasm

Release of 40 Converted Sorghum Lines From the World Sorghum Collection

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The Texas Agricultural Experiment Station of the Texas A&M University System and the Agricultural Research Service, US Department of Agriculture, announce the release of 40 combine-height, short-duration converted exotic sorghum (*Sorghum bicolor* (L.) Moench) lines for use as genetic stocks and germplasm source materials by sorghum breeders. These 40 converted lines were developed in a research program, known as the Sorghum Conversion Program (Stephens et al. 1967), conducted cooperatively by the US Department of Agriculture, Agricultural Research Service (USDA-ARS), at Mayagiiez,

Table 1. Forty sorghum converted line releases and information on original exotic cultivars, Texas Agricultural Experiment Station, Texas, USA, and the United States Department of Agriculture, Agricultural Research Service, Mayagüez, Puerto Rico, 1996.

Desig-nation[1]	SC no.[2]	PI or other no.	Local name, no., or description[3]	Origin[4] City/province	Country	Classification[5] R	Classification[5] WG	Reason for conversion[6]	Fertility reaction[7]
IS 1117C	196	248313	Satsemari		India	D	41:Durra	Div/Elite/JCS	B
IS 2680C	808	267366	J 16		Uganda	CD	40:Caud-Dur	Mod Nur (M2)	R
IS 2871C	855	267524, FAO 8469	Giza 123 S100	Giza, Orman	Egypt	D	41:Durra	Mod Nur (M2)	R
IS 3106C	606	213900	A 2789, *S. nervosum*	Through USA	Prob. China	GB	17:Doc-Rox	Mod Nur (M1)	RP
IS 3404C	629	NSL51443	Segaolane 16		Botswana	K	22:Caffrorum	Mod Nur (M)	R&B
IS 4832C	1088	NSL55458	Sundhia kana	Broarh, Gujarat	India	D	41:Durra	Midge res	R
IS 5168C	1108	NSL52327	Tella Jonna, Kagatha	Visakhapatnam, Andhra Pradesh	India	G	1:Roxburghii	Dis res	R
IS 5763C	449	591377	Karkatia Salimpur	Monghyr, Bihar	India	D	41:Durra	Mod Nur (M)	R
IS 6733C	532	NSL50503	132 AB Farako-Bâ		Burkina Faso	G	3:Conspicuum	Mod Nur (M2)	B
IS 6960C	738	570752	Nagad White, Tozi 249	Tozi	Sudan	C	33:Caudatum	Mod Nur (A)	R
IS 7436C	406	NSL54231	KA 4, Basharanba	Kafinsoli	Nigeria	G	35:Caud-Guin	Mod Nur (M)	R
IS 7714C	537	NSL50716	NG151		Nigeria	G	3:Conspicuum	Mod Nur (M2)	R
IS 8898C	1237	NSL56134	E 563 Esila	Tororo Dist.	Uganda	CK	38:Caud-Kaf	Midge res	
IS 11885C	1031	330165	Col. No. P-31	N. of Debre Sina (Shoa)	Ethiopia	DB	45:Dur-Doc	High altitude	R
IS 11930C	1158	330212	Col. No. P-104	Asmara, Eritrea Province	Ethiopia	D	41:Durra	Dis res	R
IS 12675C	184	277542	Suki PS295	Pretoria	South Africa	CK	27:Caf-Fet	Div/Elite/JCS	BP
IS 17204C	1065		CE 63-18		Senegal	C	33:Caudatum	Western Africa Elite/ OJW	
IS 17215C	1076		Line SK-MDW		Nigeria	C	40:Caud-Dur	Western Africa Elite/ OJW	B
IS 17216C	1077		Sorgho 137-62		Nigeria	C	39(1):Zerazera	Western Africa Elite/ OJW	R
IS 23492C	1302	PAB3		Gambella Market	Ethiopia	C	39(1):Zerazera	Elite Zerazera	
IS 23601C	1318	PAB124	Alangua	Chodo (53 S Gambella)	Ethiopia	C	39(1):Zerazera	Elite Zerazera	
IS 23607C	1319	PAB130	Nyaluwal, Tungo	Abobo (57 S Gambella)	Ethiopia	C	39(1):Zerazera	Elite Zerazera	
SC 1205C	1205		CE90-16-3		Senegal	C	39(1):Zerazera	Local Drought res	
SC 1212C	1212		SL-PR-32650		Venezuela	C	33:Caudatum	High yield Hegari	
SC 1320C	1220		P967083		Ethiopia	C	39(1):Zerazera	*Striga resistance*	
SC 1321C	1321		Col. El Obeid 8-1, Korky	El Obeid area, N. Kordofan	Sudan	C	35:Caud-Guin	Drought res*	
SC 1322C	1322		Col.El Obeid 8-2, Ferik	El Kharta, N. Kordofan	Sudan	DB	43:Dur-Mem	Drought res*	

Continued.

Table 1. *Continued.*

Desig-nation[1]	SC no.[2]	PI or other no.	Local name, no., or description[3]	Origin[4] City/ province	Country	Classification[5] R	Classification[5] WG	Reason for conversion[6]	Fertility reaction[7]
SC 1325C	1325		Col. El Obeid 8-5, Umm Tul	El Kharta, N. Kordofan	Sudan	C	40:Caud-Dur	Drought res*/TS	
SC 1328C	1328		Col. El Obeid 8-8, Nachatt Ahmar	El Kharta, N. Kordofan	Sudan	C	33:Caudatum	Drought res*	
SC 1329C	1329		Col. El Obeid 8-9, Gadumel Tatil	Kaba, N. Kordofan	Sudan	DC	40:Caud-Dur	Drought res*	
SC 1330C	1330		Col. El Obeid 8-10, Marg Herchir Aswad	El Kharta, N. Kordofan	Sudan	DC	40:Caud-Dur	Drought res*	
SC 1332C	1332		CSM 87		Mali	G	4:Guineense	Elite Mali Var/JFS	
SC 1333C	1333		CSM 207		Mali	G	4:Guineense	Elite Mali Var/JFS	
SC 1337C	1337		CSM 388		Mali	G	4:Guineense	Elite Mali Var/JFS	
SC 1339C	1339		CSM 414		Mali	G	4:Guineense	Elite Mali Var/JFS	
SC 1341C	1341		CSM 417		Mali	G	4:Guineense	Elite Mali Var/JFS	
SC 1345C	1345		CSM 90		Mali	G	4:Guineense	Elite Mali Var/JFS	
SC 1351C	1351		Shot Damon #2-2, N. Black	Kaduguli area, S. Kordofan	Sudan	C	33:Caudatum	Div/Elite Local/DTR	
SC 1356C	1356		Shot Damon #3-2, N. Black	Kaduguli area, S. Kordofan	Sudan	C	33:Caudatum	Div/Elite Local/DTR	

* Represents reported drought-tolerant material from dry, sandy areas in Northern Kordofan area of Sudan.

1. Designation of converted lines was obtained by adding C to the IS number used in the World Sorghum Collection. Those without an IS number were given a C following the SC number.
2. The SC number is the serial number given to the exotic variety when entered into the Sorghum Conversion Program and used during conversion.
3. The local name, number, code, or description of the exotic variety.
4. 'Origin' indicates the location of the collection if known and country of origin of each exotic line insofar as records indicate.
5. Classification of exotic line. R = Race is based on Harlan and de Wet (1972), where B = Bicolor, G = Guinea, C = Caudatum, K = Kafir, and D = Durra. WG = Working Group number and name is based on Modified Snowden's Classification by Murty and Govil (1967).
6. General reason for conversion. Modified Nursery = Modified Nursery selected by K O Rachie et al., from the World Sorghum Collection, 1963/64. M1 = representative of each classification group as described by Murty and Govil (1967); M = lines representing major variation in each group; M2 = other variations of possible breeding value; A = breeding value to Indian program; IES and JCS = I E Stokes and J C Stephens, former USDA-ARS sorghum researchers at Meridian, Mississippi, and Chillicothe, Texas; Dis res = disease resistant selected material by R A Frederiksen based on disease evaluation at ICRISAT (L R House--downy mildew, rust, leaf blight, cercospora leaf spot) and foliar reaction (bacterial stripe, cercospora leaf spot, rust, and zonate leaf spot) in South Texas; Midge res = reported midge resistance; Drought res = reported drought resistance; TS = twin-seeded; OJW = O J Webster; JFS = J F Scheuring; DTR = D T Rosenow.
7. The fertility reaction as determined from crosses between a milo-kafir cytoplasmic-genetic, male sterile (A1) and the exotic line: R = restorer (progeny all male-fertile); B = maintainer (progeny all male-sterile) PB or RP = partial restorer.

Puerto Rico, and the Texas Agricultural Experiment Station.

The converted lines were developed through a backcross procedure in which tall, long-duration tropical sorghum varieties or cultivars were converted to short-duration combine-height sorghums. Conversion is accomplished by a crossing and backcrossing program using favorable short-day photoperiods during the winter in Puerto Rico, with selection for early, short genotypes within segregating populations under long-day, summer conditions at Chillicothe, Texas. All converted lines for release are derived from four backcrosses to the original exotic variety. The nonrecurrent parent used in all cases was a short-duration 4-dwarf Martin B line, BTx406, of US origin. The exotic varieties were used as male parents in all crosses and backcrosses until the third backcross when they were used as the females in order to recover the original cytoplasm in the converted line.

The converted lines are photoperiod-insensitive, will mature normally in USA, and are short statured, generally 3- or 4-dwarf. in height, but occasionally 2-dwarf. They represent new sources of germplasm from the World Sorghum Collection and are of suitable height and maturity for use in USA and other temperate-zone areas of the world. These materials should contain new sources of such desirable traits as disease and insect resistance, drought resistance, and improved grain quality, and should be useful to breeders and other sorghum researchers as germplasm sources in developing improved sorghum lines and hybrids. Table 1 provides information on the converted lines and the original exotic varieties.

Seed will be maintained and distributed by the Texas Agricultural Experiment Station at the Texas A&M University Agricultural Research and Extension Center at Lubbock, Route 3, Box 219, Lubbock, Texas 79401-9757, USA. It will be available in germplasm quantities only. Private companies will be charged a fee of US$250 for the complete set, or US$20 per individual line. Payments should be made to Texas Agricultural Experiment Station', and should be in US dollars. Genetic material of this release will be deposited with the National Plant Germplasm System, where it will be available for research purposes including development and commercialization of new varieties/cultivars. Those receiving seed are asked to agree to supply, upon request, information about breeding behavior, desirability, and usefulness of the material and to cite it as the origin of useful derived lines.

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Pathology

Host Range of Sorghum Downy Mildew in Africa

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Sorghum downy mildew [*Peronosclerospora sorghi* (Weston and Uppal) C.G. Shaw] is a major disease of both sorghum [*Sorghum bicolor* (L.) Moench.] and maize [*Zea mays* L.] crops grown in tropical and sub-tropical regions of the world. The grain yield loss resulting from systemic infection, which causes sterility, can be devastating (Williams 1984). Collateral hosts have been implicated in the between-season survival of *P. sorghi* in the Americas (Malaguti 1977). Only species in the tribes Maydae, Andropogonae and Panicae have been confirmed as susceptible (Bonde and Freytag 1979, Karunakar et al. 1994). In Zambia, Pande and Singh (1992) found *Sorghum halepense* (Johnson Grass) infected with *P. sorghi* adjacent to farmers' fields. This indicates wild grasses may play a role in the epidemiology of *P. sorghi* in Africa. The following experiment was undertaken to investigate the host range of an isolate of *P. sorghi* from Africa.

Seed of 24 species from 4 tribes of the Graminae and one species from the Cyperaceae were collected in Nigeria. The isolate of *P. sorghi* was collected from a

Table 1. The susceptibility of different species of Graminae and Cyperaceae to conidial inoculum of an isolate of *Peronosclerospora sorghi* from sorghum, Matopos, Zimbabwe.

Host family, tribe, and species	Host reaction	Systemically infected plants
Graminae		
Maydae		
Zea mays L. var. TZESR-W	S[1]	21/25
Coix lachryma-jobi L.	R	0/8
Andropogonae		
Sorghum bicolor (L.) Moench. var. DMS 652	s	24/25
S. arundinaceum (Desv.) Stapf.	s	20/23
Hyparrhenia rufa (Nees) Stapf.	R	0/14
Andropogon gayanus Kunth.	R	0/17
Rottboelia cochinchinensis L.	R	0/13
Panicae		
Brachiaria deflexa (Schumach.) C.E. Hubbard ex Robyns	R	0/21
B. distichophylla (Trin.) Stapf.	R	0/23
B. ramosa (L.) Stapf.	R	0/9
B. lata (Schumach.) C.E. Hubbard	R	0/10
Panicum maximum Jacq.	R	0/24
Setaria barbata (Lam.) Kunth.	R	0/16
Rhynchelytrum repens (Willd.) C.E. Hubbard	R	0/21
Echinocloa colona (Linn.) Link	R	0/17
Paspalum orbiculare Forst,	R	0/14
P. conjugatum Berg.	R	0/22
Axonopus compress us (Sw.) P. Beauv.	R	0/16
Digitaria horizontal is Willd.	R	0/23
Pennisetum pedicellatum Trin.	R	0/17
P. americanum (L.) K. Schum.	R	0/25
Eragrostidae		
Eragrostis tremula Hochst. ex Steud.	R	0/11
Eleusine indica (L.) Gaertn.	R	0/18
Dactyloctenium aegyptium Willd.	R	0/22
Cyperaceae		
Cyperus		
Cyperus digitatus Roxb.	R	0/9

1. S = susceptible; R = resistant. Susceptible indicates the development of systemic symptoms in inoculated seedlings.

systemically infected sorghum crop (var. Marupantse) at Matopos Research Station, near Bulawayo, Zimbabwe. Experiments were conducted under controlled-environment conditions in the plant disease containment facility at the Natural Resources Institute, UK. Seed of each species was pregerminated in petri dishes and 24- to 48-h-old seedlings sown in 15-cm containers. Soil was sprinkled over the seedlings until they were just covered. When their coleoptiles were 1-3 cm long, seedlings were spray inoculated with a suspension of mature conidia of *P. sorghi* ($1x10^4$ conidia mL^{-1}) using a hand-held sprayer. The conidia were produced by incubating systemically infected leaves in the dark in moist containers at 22°C (leaves previously exposed to light for 12 h). After inoculation the seedlings were transferred to an incubator at 22°C for 16 h, before transfer to a greenhouse held at 26°C. Assessments were made every 7 days for 4 weeks to record the development of systemic infection.

Results of the inoculation are shown in Table 1. Of the 25 species inoculated, only three developed systemic infection (species in the tribes Maydae and Andropogonae). These were maize, sorghum, and the wild sorghum, *S. arundinaceum* (False Johnson Grass). *Sorghum arundinaceum* is widespread in Africa and could act as a source of infection for *P. sorghi* to infect sorghum or maize crops. Several other wild sorghums that were not tested in this study also occur widely in Africa and have been shown to be susceptible to *P. sorghi* (Bonde and Freytag 1979, Karunakar et al. 1994). At some locations in Africa it may be expedient to rogue collateral hosts adjacent to areas of sorghum or maize cultivation, particularly if they act as a source of conidia early in the season. They might also produce oospores which can infest the soil and infect subsequent crops.

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Entomology

Incidence of Stem Borers on Postrainy-season Transplanted Sorghum in Cameroon, Nigeria, and Chad in 1995/96

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Introduction

Postrainy-season sorghum, known as *muskwari* in Cameroon, *masakwa* in Nigeria, and *berbere* in Chad, is a very important cereal crop in Chad where it constitutes about 10% of the total cereal production and 20% of the total sorghum (rainy season + dry season) (Lotar Mougabe, Head, Systeme de l'Information du Marche, personal communication, 12 Oct 1995). *Muskwari* represents about 25-30% of the sorghum production in northern Cameroon (Djonnewa and Dangi 1988). Although its proportional production, relative to rainy-season sorghum, in Nigeria has not been determined, it is frequently the only sorghum crop available to many farmers in Borno State where it fetches a higher price than rainy-season sorghum. The grains are used to prepare a stiff porridge known as *boule* (*tuwo* or *to* in western Africa) while the stems and leaves are fed to animals, or used for fencing and as firewood. Earlier surveys had revealed that stem borers are the only important insect pests of postrainy-season sorghum in Cameroon and Nigeria (Tabo et al. 1993). Little seems to be known about the insect pests of this crop in Chad, although Versteeg (1995) reported that farmers who were involved in a diagnostic survey in the Canton de Madiagho in 1995 ranked stem borers 5th among the constraints to the production of postrainy-season sorghum in the area. The more important constraints recognized by the farmers were birds, grasshoppers, shortage of water, and storage problems. A survey was, therefore, conducted from 5 to 9 Feb 1996, to determine the incidence of stem borers on postrainy-season sorghum in Chad and parts of Cameroon and Nigeria that had not been surveyed earlier.

Materials and methods

The survey involved counting 50 randomly chosen stands of sorghum per field, and recording the percentage of plants that were infested by stem borers. Observations were made on four farms in each of Cameroon and Chad, and one in Nigeria. Symptoms of stem borer infestation that were sought included: leaf feeding, deadhearts, holes, tunnelling, and the presence of frass, larvae, and pupae in the stems. Larvae and pupae were collected and reared to adulthood on fresh sorghum stems in Kilner® jars in the laboratory. The incidence of natural enemies, particularly parasitoids, was also noted. Pupae of natural enemies were collected and kept until adult emergence. Dead larvae and pupae of the stem borer were similarly treated.

Results and discussion

The incidence of stem borers on the nine farms surveyed is presented in Table 1. Stem borer incidence was often quite high, ranging from 10% at Zigi Chokrai in Chad to 100% at Maltam and Fotokol in Cameroon. In Chad, infested stems were usually bored at the base or in the peduncle; in Cameroon and Nigeria, the stem was often riddled with tunnels and up to 15 larvae and pupae were found per stem. Consequently, the stems frequently

Table 1. Incidence of stem borers on dry season sorghum in Cameroon, Nigeria, and Chad, 1995/96.

Country	Surveys	Locations	Mean % infected	Percentage range
Chad	4[1]	6	38.3	10-71
Cameroon	4[2]	4	72.3	13-100
Nigeria	1[2] 1	70		70

1. Conducted 5, 6, and 8 Feb 1996.
2. Conducted 10 Feb 1996.

lodged due to the weakening effect of the tunnelling. Peduncle attack caused some panicles to be chaffy while others snapped off. Where the stems had been harvested, most of the stem borer larvae and pupae were found in the stubbles and the young shoots that had developed after the harvest. Where the stems were still standing, however, the insects were found in the stem tillers, within the tunnels in the stems, or between the leaf sheath and the stem. Some of the crops had been harvested at the time of the survey and birds had destroyed the panicles that were yet to be harvested; it was therefore, not possible to determine the effect of stem borer attack on grain yield. However, poor panicle exsertion, chaffiness, and snapped off panicles are bound to lead to a reduction in grain yield. One farmer at Miskine Bananan reported that he harvested only 3 bags ha^{-1} (about 300 kg of sorghum) where he had obtained 13 bags (1300 kg) in 1995. He attributed this huge loss to damage caused by birds, stem borers, and panicle pests. On this particular farm, we observed nymphs of the head bug, *Eurystylus oldi* Poppius, feeding on the panicles, and nestled under the leaf sheaths, indicating that this pest survives the dry season in this area by feeding and multiplying on this type of sorghum. Another farmer at Fotokol, who called the stem borer *tsutsa,* was aware of the incidence and damage caused by this insect, but did not know of any control measure. Stem borer infestation was higher in the traditional postrainy-season sorghum-producing areas in the three countries than in the rice-growing areas (that are flood plains but not real Vertisols) of Chad, such as Kolobo and Zigi Chokrai, where *berbere* is a relatively new crop. The stem borers collected were *Sesamia poephaga* Tarns and Bowden (Lepidoptera: Noctuidae), *Sesamia ca~lamistis* Hampson (Lepidoptera: Noctuidae), an unidentified *Sesamia* sp, and *Eldana saccharina* Walker (Lepidoptera: Pyralidae). Of the 113 stem borers collected, 19% were pupae, 81% were at different stages of larval development, and 13% were dead, indicating parasitism. Death from parasitism was higher in pupae (46%) than in larvae (5%). The percentage of larvae and pupae from which natural enemies emerged was low (less than 1%), The parasitoids identified were *Sturmiopsis inferens* Towns, *Pediobius amaurocoela* Waterston (Hymenoptera: Bulopidae), and *Apanteles sesamia* Cameron (Hymenoptera: Braconidae); while *Nesolynx phaeosoma* Waterston (Hymenoptera: Eulopidae) was recorded as a hyperparasitoid on *Apanteles.*

This preliminary survey will be followed up by a more comprehensive study of the 1996/97 dry-season crop, that will be conducted earlier in the year, possibly in early to mid-Jan 1997, before the crop is harvested. The 1995/96 crop was harvested early, probably because the scanty rainfall in 1995 adversely affected crop growth and hastened crop ripening. Farmers also harvested early to minimize acute bird damage, and to avoid the crop being grazed by cattle. Later surveys will look more critically at the effects of stem borer infestation on yield, and the incidence of natural enemies of the insect. Other dry-season hosts of *E. oldi* will also be identified.

Acknowledgments

We thank the farmers who readily allowed us to sample their fields despite the huge losses suffered by them this year. We acknowledge the help of Drs Aboubakar Ourde Ousta, Director of Direction de la recherche et de la technologic agricole (DRTA) (for making arrangements for our visit to and within Chad), Nadingar Alladoumngue, Director of CIRAD-CA in Chad, and Yagoua NDjekounkosse, Sorghum Breeder at Bebedjia, Mr Gouana Boure Oueye, Soil Scientist, DRTA, and Mr Emmanuel Owoleke, our Driver and General Assistant. We also thank Dr MC Dike of the Institute for Agricultural Research, Samaru, Zaria, Nigeria for identifying the insects.

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Survival of Overwintering Sorghum Midge in Relation to Crop Residue Destruction

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Survival of overwintering sorghum midge, *Stenodiplosis sorghicola* (Coquillett) was assessed during 1994/95 in a

field near College Station, Texas, USA. Crop residue destruction was also evaluated to determine its effect on the mortality of diapausing sorghum midges. A mean of 1,325 sorghum midges m^{-2} was estimated to have entered diapause during the 1994 sorghum-growing season. This estimate was based on 20.5 panicles in each of 20 1x1m areas in the field, 36 rachis branches on each of 30 panicles, and 1.8 diapausing sorghum midges on each of 140 rachis branches from 140 field-collected panicles. Only 0.8% of the sorghum midges that entered diapause in 1994 emerged from shredded and disked sorghum residue in 1995. Sorghum midges emerged between 11 April and 19 June, a range of 69 days. In all 386 sorghum midges were captured in three sets of 16 pyramid traps in areas where sorghum residue had been: a) shredded only, b) shredded and disked, or c) shredded, disked, and deep-plowed. The mean of 82 sorghum midges (51,244 midges ha^{-1}) that emerged from shredded, disked, and deep-plowed residue was significantly less ($F = 3.59$, $P = 0.93$) than the 185 sorghum midges (115,614 ha^{-1}) that emerged from shredded and disked residue. From the shredded only sorghum residue 119 (74,366 ha^{-1}) sorghum midges emerged. Fewer sorghum midges emerged from shredded, disked, and deep-plowed residue than from shredded only (44%) and shredded and disked residue (64%).

Evaluation of Midge-resistant Sorghum Hybrids

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Sorghum (*Sorghum bicolor*), hybrids were evaluated for resistance to sorghum midge, *Stenodiplosis sorghicola,* at Corpus Christi (CC), Texas where sorghum midge abundance was higher, and at College Station (CS), Texas, where sorghum midge abundance was moderate in 1995. Resistant x resistant, resistant x susceptible, and susceptible x susceptible controls were included. Sorghums were rated for damage based on the percentage of kernels that failed to develop. Grain yield was also assessed.

Damage rating was higher, indicating more damage by sorghum midges, at Corpus Christi (mean damage rating 4.5) than at College Station (mean damage rating 2.3). Relative differences among hybrids were similar between and across locations. Superior experimental resistant hybrids sustained much less damage than did susceptible or resistant controls. Hybrids with superior resistance (damage rating less than 3.0) at Corpus Christi were also less damaged at College Station. At both locations, hybrids reached 50% flowering within an 8-day period. Within and across locations, susceptible hybrids sustained more damage for a specific day of flowering than did resistant hybrids.

Mean grain yield at Corpus Christi ranged from 0.4 to 5.0 t ha^{-1}, and at College Station from 1.7 to 5.5 t ha^{-1}. Experimental hybrids produced from newly developed A lines yielded 4.3 (CC) and 4.9 (CS) t ha^{-1}, resistant x resistant controls yielded 4.0 (CC) and 4.2 (CS) t ha^{-1}, resistant x susceptible controls yielded 3.2 (CC) and 5.2 (CS) t ha^{-1}, whereas susceptible x susceptible controls yielded 1.3 (CC) and 3.0 (CS) t ha^{-1} (Table 1). Although differences were not consistent, resistant hybrids that were less damaged usually produced more grain. However, damage was of sufficient magnitude to identify sorghums with superior grain yield potential. Experimental hybrids produced significantly more grain than did susceptible x susceptible controls. Most differences between experimental hybrids and resistant x resistant, or resistant x susceptible controls were not significant, although experimental hybrids generally produced more grain. Experimental sorghums with female parents A91-6, A92-3, and A93-6 produced superior hybrids during at least 2 previous years, and will be released to the commercial seed industry. Hybrids with female parents designated A94 were evaluated for the first time and will be evaluated further to determine their suitability for commercial production.

Table 1. Grain yield and midge damage to sorghum hybrids at Corpus Christi (CC) and College Station (CS), Texas, USA, 1995.

Sorghum hybrids[1]	Yield (t ha^{-1})			Damage rating[2]		
	Mean	CC	CS	Mean	CC	CS
Exp hybrid	4.6	4.3	4.9	2.4	3.3	1.6
R x R	4.1	4.0	4.2	2.9	3.8	2.1
R x S	4.2	3.2	5.2	4.0	4.9	3.0
S x S	2.1	1.3	3.0	7.2	8.2	6.2

1. Exp hybrid = experimental hybrids; R x R = resistant x resistant controls; R x S= resistant x susceptible controls; S x S= susceptible x susceptible controls.
2. Damage was rated on a 1-9 scale where 1 = 0-10, 2 = 11-20, to 9 - 81-100% kernels destroyed.

Production and Management

Survey of *Masakwa* Sorghum Growing Areas in Northeastern Nigeria

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Introduction

Masakwa sorghum is a postrainy season sorghum that is grown on an estimated 102,564 km^2 mainly in the Lake Chad Basin area of Borno State, northeastern Nigeria. Similar types of sorghum can be found on extensive areas in neighboring Cameroon and Chad. There is little rainfall during this season and the crop is grown on residual soil moisture. Although this cold-tolerant crop is an important cereal in Borno State, very little information is available on the local germplasm and production practices and constraints.

The soils on which *masakwa* sorghum is grown are developed on Chad lagoonal clays underlain by aeolian sands and on alluvium of the Bama Fluvial/Deltaic complex. The pedons at Ngala and New Marte in Borno State are Typic Pellustarts, while at Bama and Gwoza they arc Vertic Ostifluvents. Calcium carbonate, manganese, and iron manganese concretions are common in these soils.

The soils are moderately to very highly base-saturated but are very low in organic carbon and nitrogen (Mordi et al. 1991).

The climate of Borno State is characterized by two distinct seasons, the wet and the dry seasons. The wet season lasts from June to September in the northern parts, and May to Oct in the southern parts of the State. The average annual temperature is about 30 °C with a maximum of 45 °C in March/April and a minimum of 15 °C during the dry Harmattan season when *masakwa* sorghum is grown.

The main objectives of the survey were to determine the *masakwa* sorghum production practices to identify the major constraints to production, and to collect local germplasm of *masakwa.* Baseline information is needed to focus research efforts on this crop.

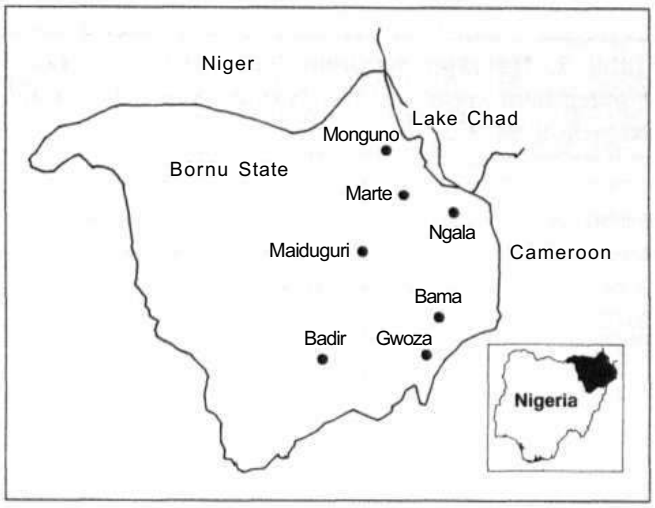

Figure 1. Local government areas surveyed in northeastern Nigeria.

Methodology

The survey areas were selected for their differences in agriculture, geography, and accessibility. Twenty four villages in 17 local government areas (LGAs) of Borno State were visited (Fig. 1). The survey was conducted using structured questionnaires which served as a check list. Discussions were held with farmers in about eight farms per village. Sorghum heads were collected from some farms.

Cultural practices of *Masakwa* sorghum production

Table 1 shows the major *masakwa* sorghum types grown in Borno State. The common types grown across the three zones are Burugukhime (red grain), Bulwalana (white grain), Adjagama (cream grain), and Tumbuna (milk grain). Based on their relative popularity in the communities and their marketability, cultivars can be ranked in decreasing order of preference as follows: Bulwalana, Adjagama, Tumbuna, and Burugukhime. However, in Bama LGA, Burugukgime was the most-preferred cultivar.

Farmers select sites for *masakwa* sorghum production on the basis of soil types, availability of land, and the amount of water stored during the wet season. Sandy clay loam to clay soils are most commonly used. Land is prepared manually, between February and May, using local implements such as cutlasses and hoes. The land is cleared of trees and shrubs. Dykes/bunds of about 0.5 to 0.75 m are constructed on the farm with the aim of impounding rainwater (which otherwise may run off), and

Table 1. *Masakwa* **sorghum types grown in Local Government** areas **and villages/towns in Borno State, Nigeria, 1991/92.**

Local Government Area	Village/Town	*Masakwa* sorghum, predominant types
Ngala	Ngala	Bulwalana
	Bugda	Burugukhime
	Dagala	Tumbuna
	Dikwa	Adjagama
Monguno	Mashillo	Bulwalana
	Njinne	Tumbuna
	Old Marte	Adjagama
		Burugukhime
Bama	Iza	Burugukhime
	Arikarari	Tumbuna
	Keri, Mbaga	Adjagama
	Walasaloderi	Adjagama
	Jagoriri	Adjagama
	Vialiya	Adjagama
	Maimiliri	Burugukhime
	Mbuliya	Burugukhime
	Banki	Burugukhime
Gwoza		
	Ngige	Adjagama
	Doric	Burugukhime
	Gwoza	Tumbuna
		Burugukhime

increasing infiltration. During early September, the new weeds that emerge are cleared and burned.

The major source of seeds is the previous seasons' harvest; secondary sources are government agencies (research institutes and agricultural development programs), and local markets. In most cases farmers raise their own seedlings, but some farmers purchase seedlings from other farmers. No farmer is engaged solely in the production of *masakwa* sorghum seedlings for sale. The nurseries are prepared in August after the heavy rains have subsided. Farmers use sunken nursery beds ranging in size from 1 x 1 m to 3 x 3 m, and usually broadcast their seeds. Seedlings are ready for transplanting about 30 to 40 days after sowing. They are uprooted from the nursery beds and tied up in small bundles which are placed in an upright position in shallow pools of water for 1 to 2 days to stimulate the development of new roots. The tops of the seedlings' leaves are cut to reduce transpiration, while their roots are trimmed with a sharp knife to facilitate transplanting. *Masakwa* sorghum is established by transplanting 4- to 5- week-old seedlings into 15 - 20 cm deep holes made manually with a heavy wooden dibbler (called - *gabgal* in Kanuri). About 200 mL of water is poured into each transplanting hole before 1 to 2 seedlings of *masakwa* sorghum are inserted. Akpose et al. (1996) reported that *masakwa* sorghum can also be direct seeded, provided irrigation facilities are available. This method of sowing and the resultant crop performance warrants further investigation.

Generally, farmers use about 10,000 plants ha"[1] but where the soil moisture status is high, especially on very heavy soils, a population of about 20,000 plants ha^{-1} **is** used. The local cultivars sown by farmers take 110 to 150 days to mature, and during this period no chemical fertilizer is used. An average yield of 800 kg ha^{-1} is recorded in farmers' fields.

Biotic constraints

The major pests of *masakwa* sorghum are birds, grasshoppers, and stem borers of the genus *Sesamia.* Birds are the most important yield-reducing agents. They attack mostly Bulwalana, Adjagama, and Tumbuna types while Burugukhime (red grain type) is rarely attacked, probably because it contains tannin. There are no cheap improved methods of controlling these pests. Farmers employ such traditional bird-scaring techniques as bird scaring by people perched on high wooden stands. They also harvest the crop early, at physiological maturity, to minimize bird damage. Covered smut *Sporisorium sorghi* (Ehrenberg) Link, downy mildew *Perenosclerospora sorghi* (Weston and Uppal) C.G. Shaw, and unidentified viruses are the common diseases. Farmers do not use measures to control these pests.

None of the farmers in the *masakwa* sorghum growing areas uses herbicides for weed control. They weed manually, using simple tools, mostly hoes and cutlasses. Weeding is done up to three times after transplanting depending on the degree of infestation. Generally, there were more weed problems in Bama and Gwoza LGAs than in the other areas surveyed.

Labor constraints

There are two main sources of farm labor: family and hired. There are, on average, four family members per household available for farm work in the areas surveyed. Hired labor is the most important source of farm labor and is mostly used for land clearing (i.e., cutting shrubs and grasses), for bunding, making holes for seedlings,

transplanting, and harvesting. At transplanting the cost of hiring labor in all the areas surveyed varied between ₦50 (US$1 -12₦ 1991) and ₦70 per person day. In areas where labor costs are low, farmers tend to establish more farm units or, bigger farms than in areas where labor costs are high.

Yield performance of *masakwa* sorghum

The yield performance of *masakwa* sorghum in four LGAs of Borno State is shown in Table 2. In Ngala LGA Adjagama gave the highest grain yield (909 kg ha^{-1}), followed by Burugukhime (687 kg ha^{-1}), while Bulwalana recorded the lowest yield (398 kg ha^{-1}). Tumbuna had the highest grain yields of 1393 kg ha^{-1} in Mongun LGA and 947 kg ha^{-1} in Bama LGA. In Gwoza LGA, Bulwalana had the highest grain yield of 786 kg ha^{-1} followed by Adjagama (699 kg ha^{1}). Burugukhime recorded the lowest grain yield at 649 kg ha^{-1}.

Cultivars seemed adapted to particular locations. Seed size was large and varied little among cultivars. Low plant densities, while minimizing interplant competition for water, placed a low ceiling on potential yields.

Table 2. Grain yields and yield components of Masakwa sorghum types in four local government areas (LGA) of Borno State, Nigeria 1991/92.

	Grain yield (kg ha^{-1})	Seeds $panicle^{-1}$	100-grain mass (g)
Ngala			
Adjagama	909	2605	4.4
Burugukhime	687	3689	4.1
Tumbuna	616	2293	3.8
Bulwalana	398	1739	4.2
Monguno			
Tumbuna	1393	2496	4.1
Bulwalana	749	2798	4.9
Burugukhime	660	2021	4.1
Bama			
Tumbuna	947	2706	5.0
Adjagama	892	2456	4.8
Bulwalana	838	1853	5.5
Burugukhime	822	2288	4.4
Gwoza			
Bulwalana	786	1929	5.6
Adjagama	699	2765	5.0
Burugukhime	649	1906	5.0

Research needs

There is a need to understand how efficiently this crop uses soil moisture and the scope to increase crop density or duration. Current transplanting methods are laborious and costly and the feasibility of direct seeding is worth further study. Labor savings will result in a larger area being cultivated. Appropriate bird control measures need to be developed. The profitability of alternatives to *masakwa* sorghum cultivation should also be examined. With appropriate land management rainy season soybean or postrainy season chickpea may be potential alternatives.

Acknowledgment

The authors are grateful to the Executive Director of ICR1SAT Western and Central Africa Region for providing special funds for this collaborative work between the Lake Chad Research Institute (LCR1) and ICRISAT. The full collaboration of farmers interviewed is also appreciated.

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Influence of Nitrogen on Seed Production of Sorghum Hybrids

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The possibilities of using nitrogen manipulation to increase sorghum hybrid seed production through improved synchronization of flowering between male and female parents have been explored by earlier breeders (Basavaraju and Bommegowda 1982, Reddy et al. 1992, Gayatri 1993).

Materials and methods

A split-plot design field experiment was conducted on a red sandy loam soil at the farm of the Seed Technology Research Project, Andhra Pradesh Agricultural University, Rajendranagar, Hyderabad, during the postrainy season 1993/94. The main plots were two parental lines of CSH 13 R (ms 296 A and RS 29) and CSH 14 (AKMS 14A and AKR 150). The subplots were nitrogen levels and methods of its application applied to the male parental lines only (Table 1).

All the female parents were given basal applications of 80 kg N ha^{-1}; and 60 kg P_2O_5 ha^{-1}. Basal applications of 40 kg K_20 ha^{-1} were made to all the parental lines. Seeding rate was maintained to give female and male parents a ratio of 6:2 in each treatment plot. The male plants were sampled at 28, 31, 35, 38, 42, 45,70, and 128 days after sowing and were analyzed for their nitrogen content (Jackson 1967). Their dry matter content was also recorded.

Results and discussion

The additional nitrogen applications in treatments, T_1,T_2, T_3, T_4 over 80 kg N ha^{-1} in treatment influenced the flowering characteristics of male plants. Those plants that received additional nitrogen flowered and completed 50% flowering earlier than the plants that received only 80 kg N ha^{-1} (Table 2). Also, flowering duration increased with additional nitrogen application (Table 2).

Table 1. Nitrogen application treatments applied to sorghum male lines.

Treatment	Method of application	Urea N (kg ha^{-1})				Total N (kg ha^{-1})
		Basal	28 DAS	35 DAS	42 DAS	
T_o	Soil	40	40	-	-	80.0
$T_,$	Soil	40	40	-	-	
	+ foliar		3.5	-	-	83.5
T_2	Soil	40	40	-	-	
	+ foliar		3.5	3.5	-	87.0
T_3	Soil	40	40	-	-	
	+ foliar		3.5	3.5	3.5	90.5
T_4	Soil	40	70	-	-	110.0

Table 2. Influence of nitrogen on flowering characteristics of male parents and hybrid seed yield, Hyderabad, postrainy season 1993/94.

Treatment	Flower initiation[1]				50%flowering				Duration of flowering		Hybrid seed yield (t ha^{-1})[3]	
	Days after sowing		N uptake[2] (kg ha^{-1})		Days after sowing		N uptake (kg ha-^{1})					
	$M_,$	M_2	M_1	M_2	M_1	M_2	M_1	M_2	M_1	M_2	F_1	F_2
T_0	81.7	67.3	55.1	53.7	83.0	69.6	55.6	54.6	13.2	14.5	1.31	1.43
T_1	80.3	66.0	61.1	57.4	81.6	68.1	61.8	58.8	13.3	15.1	1.32	1.50
T_2	80.0	65.3	77.8	73.0	81.3	67.6	78.6	75.1	14.0	15.6	1.35	1.54
T_3	79.7	65.0	84.4	77.9	81.0	67.0	85.3	79.8	14.6	15.6	1.43	1.57
T_4	80.3	66.3	72.8	70.3	82.6	68.0	74.1	71.7	13.6	15.3	1.34	1.52
CD (*P* = 0.05)												
M	0.35				0.38				0.26		0.03	
T	0.28				0.42				0.30		0.04	
P x T	0.48				0.68				0.49		0.41	

1. M_1 = RS 29 male parent of hybrid CSH 13R; M_2 = AKR 150 male parent of hybrid CSH 14.
2. Nitrogen uptake estimated from second-order regression of nitrogen content against time.
3. F_1 = CSH 13R; F_2 = CSH 14.

Using the second order regression equation of nitrogen uptake against time from sowing that the gave best fit (R^2 = < 0.95), nitrogen uptake by male plants at flower initiation and 50% flowering were estimated (Table 2).

The reduction in number of days required to flower and complete 50% flowering was related to the increase in nitrogen uptake and better utilization by plants that received more than 80 kg N ha^{-1}. Providing additional nitrogen through foliar sprays had more effect on flowering characteristics than providing it through soil application (Table 2). Response to increased nitrogen level was greater in the male parent of hybrid CSH 14 than in the male parent of hybrid CSH 13R. The negative correlation coefficients (r) between nitrogen uptake and days required for flower initiation and 50% flowering were significant (r^2 = < 0.98). The influence of different nitrogen levels and the methods of application on flower initiation and 50% flowering followed the sequence of $T_3 < T_2 < T_1 < T_4 < T_0$. The reduction in days to flower initiation, completion of 50% flowering, and prolongation of flowering in the male parents increased seed yield in the female parents (Table 2). This increase is attributed to an improvement in synchronization of flowering between the male and female parents as the female parents P_1 flowered 79.33 days after sowing (DAS) and completed 50% flowering at 81.6 DAS, P_2 flowered at 65.3 and completed 50% flowering at 67.3 DAS. The seed yield of the female parents followed the sequence of $T_3>T_2>T_4>T_1>T_0$.

The results of this experiment showed that by manipulation of nitrogen supply to the male parents at critical stages, flowering characteristics can be altered to achieve better synchronization of flowering. This results is an increase in hybrid seed production. Foliar sprays of additional nitrogen applied to male parents 2-3 times between 28 and 42 DAS could be developed into a very useful agronomic practice in hybrid seed production. However, this practice needs to be tested on other late-flowering male parents and on different soils. The optimum nitrogen level appears to be 90.5 kg N ha^{-1} applied both through soil and as three foliar sprays.

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Biotechnology

Effect of Activated Charcoal Added Medium on the Establishment of Sorghum Somaclones

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Activated charcoal (AC) is a well known adsorption agent. The positive effects of AC include the absorption of phytotoxins released by the tissues being cultured (Buter et al. 1993); and the absorption of inhibitory substances in the media (Weatherhead et al. 1978), and of gases like ethylene present in cultures (Horner et al. 1977). Its various effects on plant tissue cultures, e.g., anther culture (Buter et al. 1993), morphogenesis (Fridberg et al 1978), and shoot and root formation (Scholi et al. 1981) have also been studied. In our attempts to generate somaclones in grain sorghum genotypes, the somaclones generally had a low establishment rate mainly due to an underdeveloped root system. Some of the genotypes also produced a visible amount of such inhibitory substances as tannins in the form of browning of callus and medium, that needed frequent subculturing.

Considering these ameliorative effects, some media for routine use have been developed incorporating AC (in Anderson's pretransplant medium). Due to the problems encountered in the production of sorghum somaclones, we studied the effects of AC added medium on regenerating calli. Grain sorghum genotypes SPV 462, SPV 475, and 296B were studied. The callus regeneration method described by Murty et al. (1990) was used. Callus was induced from immature inflorescence on LS medium containing 2.5 mg L^{-1} 2,4-D incubated for 3 weeks in the dark at 27°C. Regeneration was achieved using callus incubated on MS medium with 1AA S mg L^{-1}, NAA 2 mg

Table 1. Comparison of growth parameters of somaclones regenerated in MS medium with (AC+) and without (AC-) activated charcoal, National Research Centre for Sorghum, India, 1994.

	Root length (cm)		Shoot length (cm)		Regenerants (%) with more than two equally grown tillers		Regenerants (%) surviving after transplantation	
Genotype	AC-	AC+	AC-	AC+	AC-	AC+	AC-	AC+
SPV 462	1.47a[1]	2.80b	7.47a	11.30b	78.7 (75)[2]	31.2 (80)	30.8 (78)	87.3 (103)
SPV 475	1.90a	3.60a	9.40a	9.90a	82.1 (67)	32.0 (75)	19.0 (74)	65.3 (49)
296B	1.30a	3.60b	4.90a	6.90a	100.0 (56)	54.5 (88)	37.2 (51)	83.3 (72)

1. Genotypes followed by the same letter were not significantly different at P=0.05 for that character.
2. Figures in parentheses represent the number of regenerants in each of the treatments.

L^{-1}, kinetin 0.2 mg L^{-1} and a 16 h light day^{-1} regime. The developing embryoids were separated and incubated on the establishment medium that consisted of MS with 3 g AC L^{-1}. Control treatments were maintained without addition of AC. The regenerants were observed for growth parameters after 45 days of culture on the establishment medium.

The results (Table 1) indicate that addition of AC to the regenerating medium increased the length of roots in all the genotypes, and significantly so in the case of SPV 462 and 296B. The length of the shoot also showed a positive trend in all the genotypes, particularly in SPV 462. There was a decrease in the number of tillers in the AC added medium and as a consequence, only a few sturdy regenerants emerged from the precursor callus. The regenerating precursor calli did not turn brown in the presence of AC, as was observed in the medium without AC. These characters cumulatively contributed to obtaining regenerated somaclones with better establishment as reflected in the percentage of full grown somaclones (Table 1).

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Use of Nitrous Oxide for Chromosome Doubling in Sorghum

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Nitrous oxide (N_2O) was used to induce sorghum tetraploids because, as is evident from the literature, muta-

tions have not been found after N_2O treatments, in contrast to colchicine, which frequently induces mutations.

Usually N_2O is applied to double the plant chromosome number at the first division of the zygote. We treated plants of sorghum Milo 10 grown in (pots) with N_2O under 5-7 atm pressure for 17-27 h and the treatments commenced 12-22 h after pollination.

Some plants were emasculated and artificially pollinated before treatment. However, preliminary embryological research had shown that the processes of fertilization and the first mitosis in the resulting zygotes do not occur simultaneously in sorghum flowers that have been emasculated and artifically pollinated. Even after 24 h some flowers can be observed in the initial stages of fertilization, whereas in others there are polynucleate endosperm and 4-celled embryos (Larina and Tsvetova 1986). Simultaneous pollination of all the flowers, therefore, probably does not secure any advantage. So, the majority of plants being used were self-pollinated. On such plants we marked the flowers that opened between 0900-1100 with oil paint and excised all the other flowers in a panicle.

On treated plants we observed seed set in artificially pollinated panicles; the highest seed set being 54%. In selfed panicles it varied from 53 to 83%. Side by side with normal grains very small grains were formed. Grains of normal size, but without embryos, were also noted, in some cases as many as 14%.

Ten percent of the seedlings were cytologically examined from selfed and artificially pollinated treated plants. Six tetraploids (10%) were found, among the 60 grains examined from the progeny of selfed plants.

In the progeny of some treated plants diploid sedlings were found alongside the tetraploid seedlings. These diploids had irregular ana- and telophase, polynucleate and tetraploid cells in their root tips. The frequency of these mitosis disturbances was not more than 5-7%. These types of disturbances were not observed earlier in the offspring of colchicine-treated plants.

Plants of four other varieties and lines were also treated with N_2O. Among the 158 seedlings of their offspring studied, only one tetraploid was found in Sudan Grass line K 16/1E. Mitosis disturbances, such as those noted in Milo 10, were observed in some plants.

The N_2O-derived tetraploids of Milo 10 were shorter than the diploids. Panicle head length was slightly decreased, but in some families this difference was not significant at the 5% level. Seed set ranged from 79.6%' to 86.4% in diploids in different years, whereas tetraploids ranged between 20.5% and 40.3%. The 1000-seed mass of tetraploids exceeded that of the diploids (Table 1). The pollen grain diameter of diploids varied from 37.60 to 58.30 mμ, whereas that of the tctraploids was 41.70-66.80 mp. The dates of onset of anthesis were similar in both tetraploids and diploids.

Table 1. Characteristics of diploid and tetraploid plants.

Character[1]	2n	4n
Plant height (cm)	90.42±1.88	68.25±1.20***
Panicle length (cm)	15.51±0.50	14.49±0.21
Seed set (%)	82.97±1.77	30.43±2.45***
1000-seed mass (g)	35.40±0.27	38.90±0.70**

1. Mean data taken from 1991-94;
** Significant at 5% level
*** Significant at 1% level

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Selection for High Frequency of Aposporous Structures in Sorghum

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A sorghum line, AS-1, with partial male fertility and elements of apomixis was obtained from the initial stages of tissue culture of a plant with cytoplasmic-genetic male sterility (CMS) (Enaleeva et al. 1994, Elkonin et al. 1995). Additional structures varying in size and in number, and the disposition of nuclei were observed in the ovules of plants of this line alongside the common meiotic embryo sacs (ESs). These structures were either large cells with a single nucleus or multinuclear formations; sometimes, they resembled ESs with normal or abnormal differentiation. Parthenogenesis was rare in such aposporous or meiotic ESs. It was established that the ability to form aposporous structures (APS) was inherited and expressed in several generations. Its expression varied significantly among different plants (2-53%). We have initiated a study to increase and stabilize the APS trait by

selecting plants that showed a high APS frequency. The progenies of such plants have been selected and used for reproduction for four generations.

From cytoembryological analysis based on 50 ovules, we found 8% APS in the R_4 generation. The average APS condition, after selection in R_5 was 11.5%, and in R_6, it was 24.5%. Further selection for high APS in R_6 resulted in R_7 progeny with 35.7%. However, in the unselected progenies, the mean frequency of APS was only 7%. This indicated that selection tor APS was highly effective. This selection increased the apomictic potentials of the line AS-1, which resulted in autonomous development of embryos from meiotic or aposporous ESs.

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Influence of Nitrogen Sources on Induction and Growth of Embryogenic Callus of Sorghum

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Amongst the many factors that control the embryogenic potentials of cultured plant tissues, the level and ratio of different sources of nitrogen are most important. In order to optimize the composition of the medium for growth of embryogenic sorghum cells, we studied the influence of different sources of nitrogen on the induction and proliferation of embryogenic callus (EC) of several sorghum cultivars including Volzhskoye 2, Milo 10, and Rannee 7.

Fragments of young panicles were cultured on Murashige and Skoog (MS) medium and its 8 modifications with different levels and ratios of NH_4+ (370, 1130, 2250 mg L^{-1}) and NO_3 -(2500, 4500, 8200 mg L^{-1}) ions, with or without organic nitrogen (1-asparagine, 1 g L^{-1}, and 1-proline, 2 g L^{-1}). The differences in NH_4^+ and NO_3 -concentrations were obtained by changing the concentrations of KNO_3 and NH_4NO_3 in the basal MS medium. All the media contained 3% sucrose and 1.0 mg 2.4-D L^{-1}.

We found that addition of amino acids to basal MS medium was more effective than increasing the concentration of inorganic nitrogen on EC growth (Table 1). Compared with MS, the medium with doubled concentration of NO_3-, trebled the concentration of NH_4+, and the addition of organic nitrogen (M2AP medium) was more effective in stimulating EC growth than MS, and MS with amino acids. The inorganic nitrogen composition of M2AP medium was effective only when the amino acids, asparagine and proline were added to it. A similar synergistic effect of increased levels of inorganic nitrogen and amino acids on the stimulation of somatic embryogenesis has been found in tissue cultures of carrot and alfalfa (Wetherall and Dougall 1976, Stuart and Strickland 1984).

Increasing the inorganic nitrogen content (M22AP medium) had little effect on EC growth. The increase of concentration of NO_3 -only (M21AP medium) or NH_4^+ only (M23AP medium) in the media supplemented with organic nitrogen was also less effective. This shows that both sources of inorganic nitrogen (NH_4+ and NO_3-) and optimal NH_4+ : NO_3- ratio are important for EC growth in sorghum. The necessity of an optimal NH_4^+ : NO_3^- ratio for the induction and growth of embryogenic cells has also been shown in the tissue culture of other plant species (Mordhorst and Lortz 1993). Cultured sorghum tissues require a far higher NH_4^+ level for intensive EC proliferation than other plant species. The proportion of EC in total callus was extremely high in cultures grown on all the media with increased NH_4^+ levels and with added amino acids.

The medium M2AP, with increased inorganic nitrogen and addition of amino acids, was also favorable for the induction of EC in different sorghum cultivars (data not presented). However, for subculturing induced EC, MS medium with 2,4-D and 6-BAP, or N6 medium with 2,4-D, asparagine, and proline were superior to M2AP.

The EC developed on all the media tested in these experiments was compact. Evidently, changes in the level of inorganic nitrogen and the NH_4^+ : NO_3 - ratio in the MS medium, together with the addition of asparagine and proline does not result in the formation of friable embryogenic callus such as that which can be obtained in sorghum grown on the N6 medium supplemented with the same amino acids (Elkonin et al. 1995).

Table 1. Influence of nitrogen sources on growth of embryogenic callus (EC) in prime cultures of young panicles of sorghum cultivar Volzhskoye 2.

Medium	Ion composition (mg L^{-1}) NH_4+	Ion composition (mg L^{-1}) NO_3^-	Organic nitrogen	Total mass of callus[1] (mg)	EC (mg)	EC (%)
MS[2]	370	2500	-	194.8 ab	38.6a	21.02
MSAP	370	2500	A[3] + P[4]	441.6 ef	129.2 ab	28.59
M2	1130	4500	-	111.6a	38.2 a	26.24
M2A	1130	4500	A	374.6 de	139.0 b	37.74
M2P	1130	4500	P	199.4 ab	80.6 ab	40.65
M2AP	1130	4500	A + P	501.2 f	260.8 c	51.85
M21AP	371	4495	A + P	323.2 cd	99.4 ab	32.26
M22AP	2250	8160	A + P	127.4 a	64.8 ab	48.54
M23AP	1125	2476	A + P	272.8 bcd	117.2 ab	44.07

1. Means of five replications. Means with different letters are significantly different (5% level), according to Duncan's Multiple Range Test.
2. MS = Murashige and Skoog medium;
3. A = aspargine (1g L^{-1}); and
4. P = proline (2 g L^{-1})

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Androgenic Response of Cultured Anthers and Microspores of Sorghum

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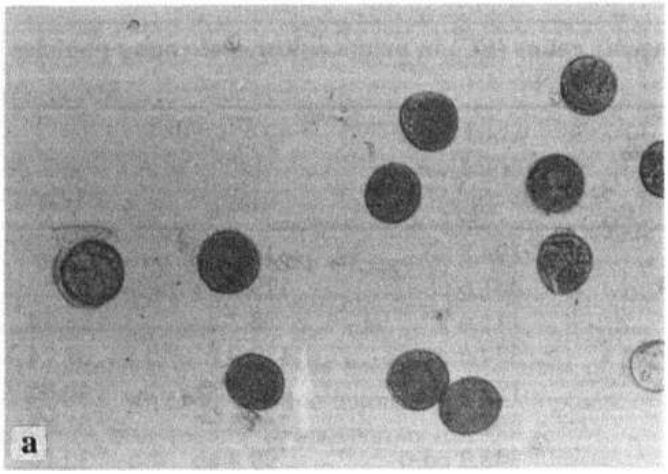
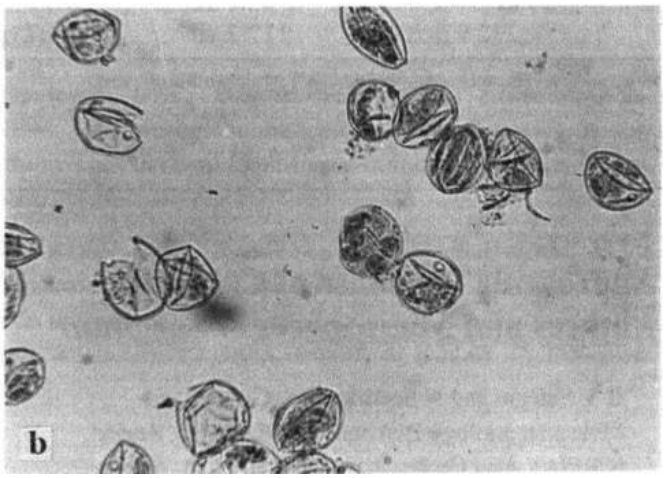
Introduction

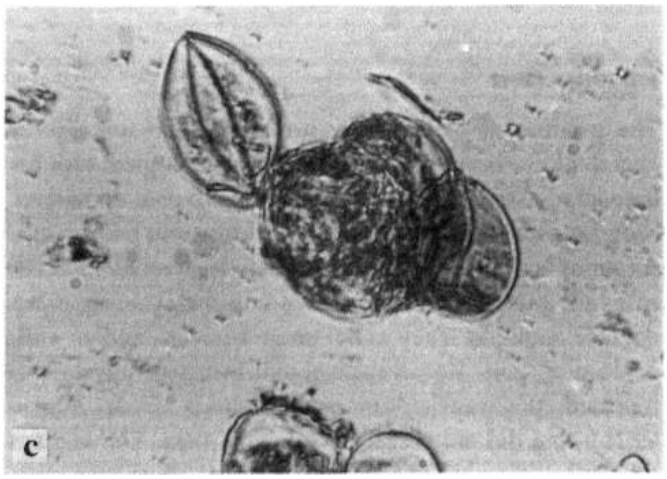
The production of haploids through anther and microspore culture is an intermediary biotechnological tool for breeders, geneticists, and map makers. To date there have been four serious attempts to produce haploid plants from sorghum anthers cultured in vitro. However, in most cases the plants regenerated from culturing anthers were not true haploids. They either arose from the anther wall, or were albinos. Kumarvadivel and Rangaswamy (1994) reported the regeneration of haploids from hybrid CSH 5, but did not present cytological data. The authors were unable to reproduce their results. Therefore, various factors that could affect androgenic response in sorghum have been studied.

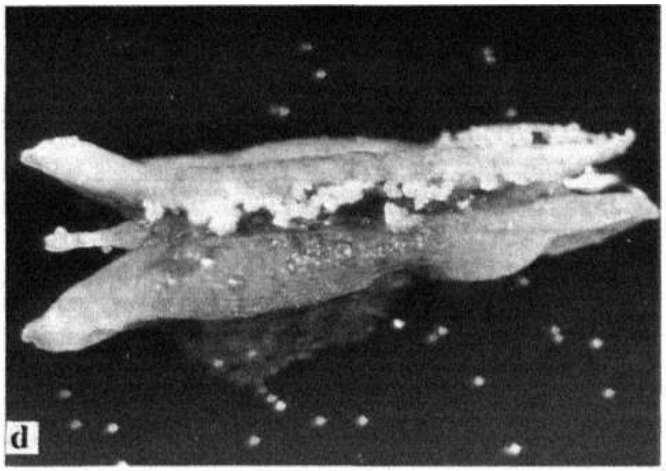
Materials and methods

Seeds of three *Sorghum bicolor* (L.) Moench hybrids CSH 5 (2077 A x CS 3541), CSH 9 (296 B x CS 3541), CSH 12R (296 B x M 148 138) were sown in pots and grown in









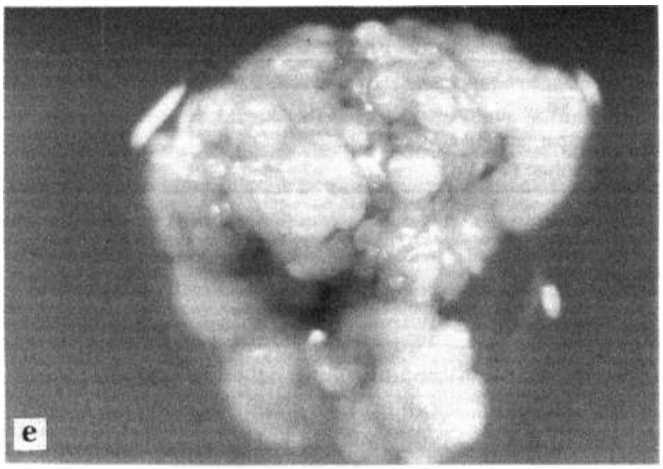


Figure 1. Haploid cultures of sorghum.
a. Microspores at uninucleate stage.
b. Dividing microspores after 15 days of culture on MS medium.
c. Multicellular divisions leading to formation of pro-embryoids.
d. Calli growing from within the anthers on MS medium.
e. Irregular masses of calli after 30 days of culture on MS medium.

a greenhouse. Their panicles enclosed in their leaf sheaths were harvested, and the developmental stage of the microspores in the anthers assessed by staining with 1% acetocarmine. Only the panicles with mid- to late-uninucleate stage microspores (Fig. la) were retained. The panicles were removed from the leaf sheaths and surface-sterilized with 0.1% mercuric chloride for 3 min. Anthers with uninucleate microspores were dissected out of 10 spikelets and plated on MS, B5, and N6 media with 0.5 mg L^{-1} kinetin (KN), 2.0 mg L^{-1} NAA, and 2.0 mg L^{-1} 2,4-D and incubated at 26 °C. Microspore division and callus formation were observed as measures of androgenic response.

Results

Effect of pre-culture conditions

Of the three hybrids studied, the maximum callus induction frequency was observed in CSH 9 (60% of anthers plated) followed by CSH 5 (20-30%). CSH 12 R showed the lowest response (15-20%). The uninuclear vacuolated microspores were most responsive as inferred from the rate of cell division. Cultures of anthers with micro-

spores at earlier (small cells without vacuoles) or later (binucleate microspores) stages did not show any androgenic response. The highest response was obtained when material was incubated at 26°C. Pretreatment of panicles at low temperatures (4°C, 6°C, 8°C, and 10°C) showed no advantage. Unsuitable pretreatment could inhibit callus production.

Culture conditions

By the 12th day, the anthers plated on all the three media started turning black (more on B5 and N6 media than on MS medium). Acetocarmine squashes of anthers revealed degeneration of microspores in B5 and N6 media while they were healthy, and showed divisions on MS medium (Fig. Ib). The vegetative cells of the microspores take part in the formation of multicellular microspores while the generative cells are quiescent. Microspores grown on medium with 0.8% agar showed more divisions (up to 60%) than those grown in the liquid medium (15-20%). As carbon source, sucrose was more effective in inducing divisions (50-60% of the microspores dividing) than maltose (15-20%). Increase in sucrose concentration from 3% to 6%, marginally increased the percentage of responding anthers, but a further rise in concentration to 10% or 12% decreased this percentage.

Comparison of auxins, and effect of kinetin

Two auxins (NAA, and 2,4-D) were used at 2.0 mg L^{-1}. Acetocarmine squashes of sorghum anthers observed after 15-20 days of culture revealed that 2,4-D or NAA (2.0 mg L^{-1}) alone could not induce divisions, but that the combined effect of 2,4-D and NAA at 2.0 mg L^{-1} could induce divisions. When 2,4-D and NAA at a concentration of 2.0 mg L^{-1} was used in combination with 0.05,0.1, 0.15, and 0.2 mg L^{-1} concentrations of kinetin (KN), the percentage response increased. A maximum number of multicellular microspores (pro-embryoids) was observed at 0.2 mg KN L^{-1} (Fig. Ic). Microcalli were found growing from within the anthers after 20-30 days of culture (Fig. 1d). These microcalli were transferred to MS medium, and irregular masses of calli were observed after 30 days of culture (Fig. Ie). The addition of such supplements as coconut milk and charcoal had no effect on the division of microspores or induction of callus.

Conclusions, and suggestions for future work

The above results are encouraging, and justify additional research to produce sorghum haploids. Microspore cultures should be emphasized more than anther cultures because they may be less dependent on genotype, or on the cultural conditions under which the mother plant is grown.

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Food and Feed Quality

Use of Popped versus Malted Sorghum Flour in Supplementary Foods for Children

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The use of malted sorghum (*Sorghum bicolor* L. Moench) flour in supplementary foods for children has been well established (Gopaldas 1992). However, the long processing time required to prepare malted sorghum flour limits the use of the malting technique as a routine way to prepare supplementary foods at household level. The technique of popping is quick, relatively simple, and improves the digestibility of starch in grains. Even though popped sorghum is a traditional snack food in certain parts of India, popped sorghum flour has not yet been used to develop supplementary foods. The present study was undertaken to compare the sensory quality of supplementary foods based on popped sorghum flour with that of malted sorghum flour to find out if popped sorghum flour is suitable for use in supplementary foods for children.

Sorghum grains of genotype SPH 509 were obtained from the Department of Plant Breeding, College of Agriculture, G B Pant University of Agriculture and Technology, Pantnagar. Popped sorghum flour was prepared by popping the grains in common salt (Singh and Srivastava 1993) before milling. Malted sorghum flour was prepared by steeping the grains for 12 h and subsequently by sprouting them for 48 h by the traditional household method (Gopaldas 1992). Mixes were prepared by combining popped or malted sorghum flour, roasted legume

Table 1. Sensory quality characteristics of supplementary foods based on popped and malted sorghum flour.

Supplementary food (gruel)	Taste (score)[1]	Aroma (score)[2]	Overall acceptability (score)[1]
Popped sorghum + groundnut	3.75	2.25	3.50
Popped sorghum + chickpea	4.00	2.62	3.75
Malted sorghum + groundnut	3.50	2.25	3.12
Malted sorghum + chickpea	3.37	2.12	3.12
CD at 5%	0.73	0.68	0.71

1. Scored for taste, and overall acceptability on a 1-5 scale where 5 = good; 4 = fair; 3 = average; 2 = bad; and 1 = very bad.
2. Scored for aroma on a 1-3 scale where 3 = pleasant; 2 = moderate; 1 = unpleasant.

flour, and sugar. The protein contents of various mixes ranged from 10.6 to 12.5 g and their energy contents from 380 to 425 kcal per 100 g. The sensory quality of gruels made from the mixes was scored by a semi-trained panel of 8 members. Analysis of variance was used to sort out variance among characters (Snedecor and Cochran 1968).

The results show that supplementary foods based on popped or malted sorghum flour did not differ significantly (P = 0.05) in the scores obtained for taste, aroma, and overall acceptability (Table 1). The overall acceptability of all the supplementary foods was above average indicating that popped sorghum flour could be used instead of malted sorghum flour in the routine preparation of supplementary foods for children.

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Nutritional Quality of 15 Glossy Sorghum Forages at Different Growth Stages in Irrigated and Rainfed Situations

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Several studies have demonstrated that the glossy trait in sorghum is related to biotic and abiotic stress-resistance factors (Maiti et al. 1984, Maiti 1993). Some glossy lines have high forage and grain production in irrigated and rainfed situations (Maiti et al. 1994). This study investigated the nutritional quality of 15 glossy lines at different growth stages under both irrigated and rainfed situations in Marin, Nuevo León, Mexico, in August 1990 (Francisco 1994). The glossy genotypes included in the study were IS 5604, IS 1034, IS 4663, IS 18390, IS 2205, IS 5484, IS 8315, IS 5642, IS 1096, IS 8977, IS 5587, IS 4776, IS 5622, IS 5567, and IS 2146. These genotypes were initially selected for their good agronomic characters. The experimental design consisted of 15 genotypes and 3 replications in a completely randomized design. The aerial parts of five plants were collected from each replication at intervals of approximately 15 days starting 31 days after emergence (DAE) (31, 46,61, and 76 DAE). The samples were dried in an oven at 80°C for 5 days. A nonreplicated bulk mixture of 3 replications was analyzed for ash, crude protein, dry matter, neutral detergent fiber, acid detergent fiber, in vitro digestibility of dry matter, and organic matter following standard AOAC guidelines (Goering and van Soest 1970, Tilley and Terrey 1963). Genotypes showed large variations in different nutritional components at different growth stages. Table 1 shows the average values of nutritional components at 31 and 76 DAE under rainfed conditions. Protein contents were very high in all genotypes at 31 DAE, but were drastically reduced at 76 DAE (Fig. 1). Protein and ash concentrations decreased with the age of the crop in both conditions. In general, neutral detergent fiber (NDF) increased with age of the crop in irrigated conditions, but decreased in rainfed situations, probably due to chance. Acid detergent fiber (ADF) increased with growth stage under both irrigated and rainfed situations. Differences were observed in the in vitro digestibility of dry matter (IVDMD) between the two systems, with higher digestibility occurring under irrigation. In vitro di-

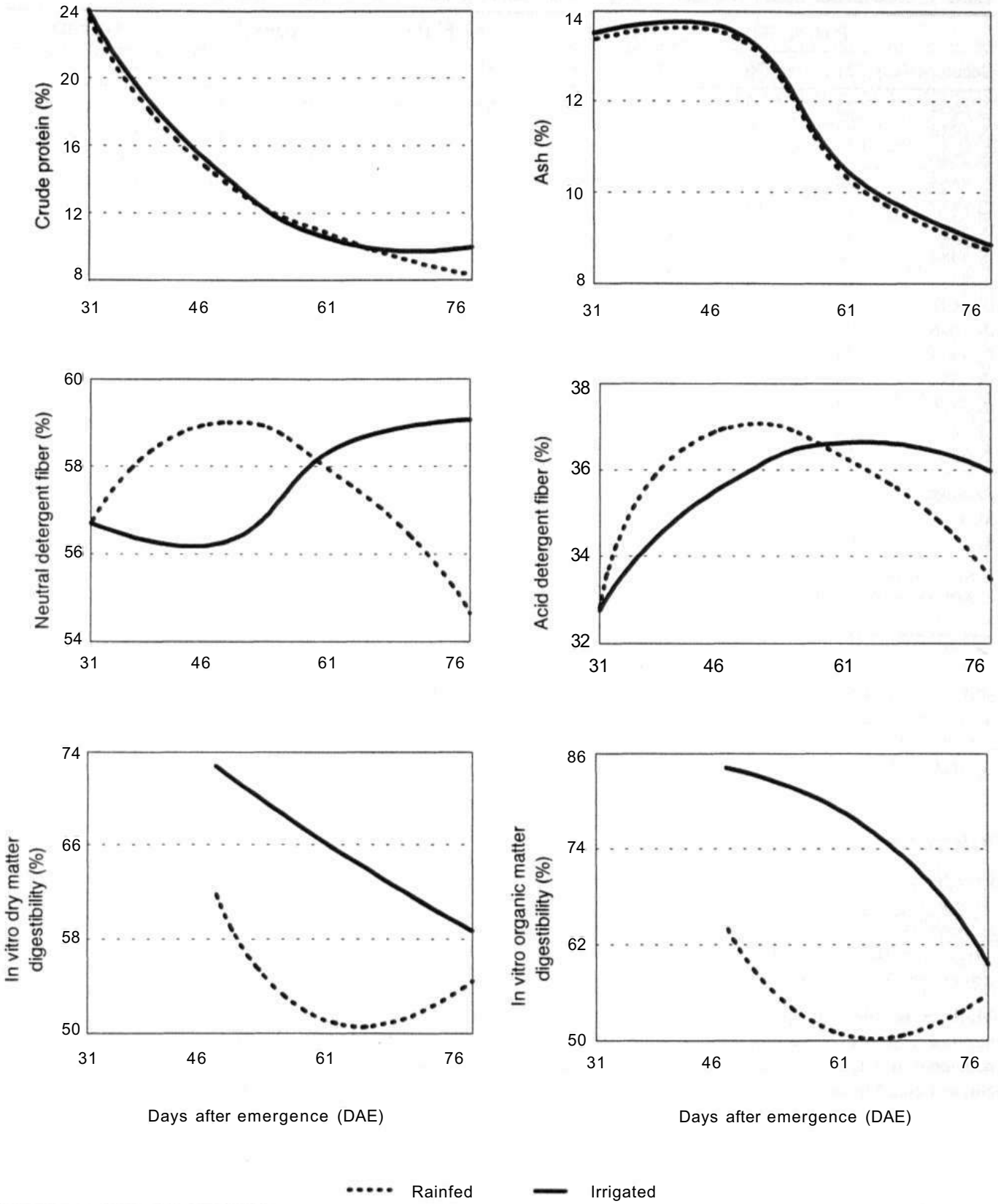

Figure 1. Effect of rainfed and irrigated systems on forage quality of glossy sorghum as measured by percentage crude protein, ash, neutral detergent fiber, acid detergent fiber, in vitro dry matter digestibility, and in vitro organic matter digestibility.

Table 1. Nutritional values of 15 glossy sorghum stovers at 31 and 76 DAE under rainfed conditions.

	Protein (%)		Ash (%)		NDF[1] (%)		ADF[2] (%)		IVDMD[3]	
Genotype	31	76	31	76	31	76	31	76	46	76
IS 5604	23	8	14	9	54	52	30	32	65	55
IS 1034	24	9	10	9	55	55	34	33	65	57
IS 2146	23	7	12	9	62	54	41	36	64	53
IS 4663	24	8	16	10	54	54	35	34	65	52
IS 18390	24	10	12	9	54	56	35	33	70	58
IS 2205	23	7	13	8	58	54	35	32	68	58
IS 5484	24	9	10	8	57	54	36	33	62	51
IS 8315	25	8	14	8	56	51	32	31	56	52
IS 5642	23	9	10	9	57	59	29	36	62	54
IS 1096	23	8	15	11	55	55	31	34	64	57
IS 8977	24	9	16	9	60	52	32	31	65	64
IS 5587	23	8	11	9	58	52	30	34	63	48
IS 4776	24	8	15	8	58	52	29	32	45	55
IS 5622	24	8	15	9	54	58	32	35	54	54
IS 5567	22	8	17	8	58	58	31	36	60	49
Average	24	8	14	9	57	55	33	33	62	54
Max	25	10	17	11	62	59	41	36	70	64
Min	22	7	10	8	54	51	29	31	45	47

1. NDF = neutral detergent fiber.
2. ADF = acid detergent fiber.
3. IVDMD = in vitro digestibility of dry matter.

gestibility decreased with growth stage. In general, protein content, NDF, ADF, and ash contents were no different in either moisture condition, but digestibility decreased in rainfed situations.

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Genetics and Plant Breeding

Allelic Relationship of Pearl Millet Inbreds vis-a-vis Cytoplasmic Genie Male Sterility

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The A_1 cytoplasm of pearl millet originally released as Tift 23A (Burton 1965) was a valuable tool for producing commercial F_1 hybrids, but because male-sterile lines succumbed to diseases, particularly downy mildew, and CMS A, mutated to normal cytoplasm, it became necessary to search for new systems. At least five different male-sterility systems representing A_1, A_2, A_3, Ex-Bornu (Gero, Maiwa), *Violacewn,* and A_4 (*monodii*) have been reported, all with a different major gene control. The F_2 segregation of fertility-restoring factors is not clear. Many cases appear to be influenced by minor genes and environments. Despite this, a number of new CMS lines have been developed, most of them have A_1 cytoplasm (Kumar and Andrews 1984).

To develop a new male-sterile line it is imperative to identify a sterile source and its maintainer line. In our efforts to develop new male-sterile lines we used some male-sterile lines received from the Genetic Resources Unit of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in 1983, and crossed them with elite inbreds maintained at Haryana Agricultural University (HAU), Hisar. Among these lines was DSA 134 (an African source of a male-sterility system). This line is early-maturing, bold-seeded, has a bold head, and appears to be a promising male-sterile line.

A number of inbred lines maintained in the HAU pollinator nursery were crossed with DSA 134A, they were found to exhibit maintainer characteristics while these inbreds effectively restore the fertility of hybrids in the A, system male-sterile lines, MS 5141A, MS 5054A, MS 3383A, MS 111 A, MS 843A, MS 842A, and MS 81A, etc. A question thus arose as to whether the inbreds maintaining male-sterility possessed similar genes to those in the background of the African source of male sterility. The inbreds that maintained sterility on DSA 134 were quite diverse in many characters, but four of them—H 90/4-5, H77/833-2, HC 715, and H 77/121—are agronomically very desirable lines. They were chosen for a study of the allelic relationship of these inbreds in the background of the African source of male sterility. H 90/4-5, is an early-maturing, downy mildew resistant, medium-tillering type. It stays green longer, is a profuse pollen producer, has medium-sized seeds and is a good combiner. H 77/833-2, the restorer of HHB 46 (MS 5141 female), HHB 60 (MS 81A), HHB 67 (extra-early released hybrid with MS 843A as female parent), HHB 68 (another extra-early hybrid with MS 842A as female parent) is the male parent of many early- to medium-maturing hybrids in the pipeline. It has a thin stem, high tillering capacity, narrow leaves, is a profuse pollen producer, and very good combiner. This genotype also possesses resistance to drought and salinity. H 77/121 and HC 715 are very high-tillering types, that flower early. Four inbreds H 90/4-5, H 77/833-2, H 77/121, and HC 715 were chosen for their desirable agronomic diversity. They merit conversion into male-sterile lines, and were crossed in diallel in all possible combinations. These inbreds were also crossed with DSA 134 B. The parents, F_1 diallel crosses, and F_1's of the inbreds pollinated with DSA 134 B, were crossed again on DSA 134 A. The resulting hybrids were grown for evaluation of their sterility reaction.

Interestingly, the plants in these types of crosses fully maintained their sterility. They did not shed pollen or set seed under bags. To further confirm that the reaction of these inbreds was truly sterile, and that the locus/loci conferring sterility were allelic in nature, the same three types of crosses were again crossed with DSA 134 B. The resultant crosses were grown in non-replicated single-row plots, 3-m long. They were evaluated for their fertility reaction by taking observations on anther dehiscence and the amount of seed set under bags on all the plants in a row. Again the pollen was not shed, nor was there any seed set under bags on any of the plants of the six types of crosses except for 0.01% seed set in DSA 134Ax(H 904-5) and DSA 134Ax(HCxH 77/121). Nevertheless, seed set on the six types of crosses when open-pollinated was good (59.2% to 95.5%). No differential reaction in the fertility pattern of various types of crosses indicates that these inbreds carry the same alleles for the male-sterility locus in the background of this African source of male sterility.

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Inheritance of Male Fertility Restoration in Pearl Millet

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The A_4 system of cytoplasmic-nuclear male sterility (CMS) in pearl millet [*Pennisetum glaueum* (L.) R. Br.] is more stable in its male sterility and produces a higher frequency of male sterile hybrids than the commercially used A_1 CMS system (Hanna 1989). This greatly increases the utility of the A_4 CMS system in breeding genetically diverse and stable male-sterile lines (A-lines). However, it also means that greater efforts will be required to breed restorers of the A_4 CMS system than that of the A_1 CMS system. An understanding of the inheritance of male fertility restoration will be useful in breeding restorer parents of this new CMS system. In a testcross nursery grown during the 1994 dry season at the ICRISAT Asia Center, we observed that a hybrid between $81A_4$ and 834B was male-fertile, with excellent pollen shedding and selfed seedset. 834B is a maintainer line of an early-maturing A_1-system A-line (834A). It is of medium height, has high seedling vigor, large seeds (12 g 1000-seed^{-1}), a high level of resistance to downy mildew [*Sclerospora graminicola* (Sacc.) Schroet], large and bristled but loose panicles, and good general combining ability. Therefore, this line can be directly used as a restorer parent of the A_4-system A-lines and an elite source of restorer gene(s).

We studied the inheritance of fertility restoration in a cross between $81A_4$ and 834B. Six F_1 plants in this cross were selfed to produce F_2 progenies, and backcrossed on $81A_4$ to produce BC_1 progenies during the 1995 rainy season. About 200-240 plants of each F_2 progeny and 100-150 plants of each BC, progeny were visually evaluated for pollen shedding during the 1996 dry season. Plants shedding pollen were classified as fertile (F), and those not shedding pollen as sterile (S).

The aggregate segregation ratio in the F_2 generation did not fit a 3F:1S ratio, expected of a monogenic inheritance, and the segregation pattern across the six progenies was heterogeneous (Table 1). Three progenies gave a good X^2 fit to 3:1 ratio (P = 0.10-0.75). The other three progenies did not fit a 3:1 ratio, and had an excess of sterile plants. Male sterility in pearl millet has been shown to be more pronounced in the dry season than in the rainy season (Rai and Hash 1990). The aggregate segregation ratio in the BC_1 generation gave an excellent fit to a 1:1 ratio (P = 0.75-0.90) and the segregation pattern across the six progenies was homogeneous (P =0.05-0.10). These preliminary results indicate that 834B carries a single dominant gene for male fertility restoration of the A_4 CMS system.

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Table 1. Segregation for pollen fertile (F) and sterile (S) plants in F_2 and backcross (BC_1) generations of a pearl millet cross ($81A_4$ x 834B), ICRISAT Asia Center, dry season 1996.

		Plants		Expected			Heterogeneity	
Generation	Progenies	F	S	F:S ratio	X^2	P	X^2	P
F_2	6	915	391	3:1	17.0	<0.01	23.0	<0.01
BC_1		354	360	1:1	0.1	0.75-0.90	9.6	0.05-0.10

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Recurrent Selection Does Not Increase Pathogenicity of *Moesziomyces penicillariae* to Trichomeless Pearl Millet

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Isolates of the smut fungus *Moesziomyces penicillariae* (Bref.) Vanky differ in their pathogenicity to pearl millet (Wilson and Bondari 1990). The potential of *M. penicillariae* to adapt to pearl millet with resistance conferred by the *tr* allele (Wilson 1995) was evaluated.

Two bulk cultures of the pathogen were established. Sori were collected from naturally infected *TrTr* and *trtr* pearl millet in the field in 1992. Teliospores from 15 sori collected from either genotype were cultured on individual plates of V8®-juice agar. Twelve uncontaminated cultures were bulked according to whether they were collected from *TrTr* or *trtr* plants. These bulk cultures were designated TR-0 and tr-0.

Five cycles of inoculation with Tr-0 and tr-0 were performed. Greenhouse-grown Tift 23DA (*TrTr*) and Tift 23DAS (*trtr*) were inoculated by misting five panicles with either TR-0 or tr-0 (1.4×10^7 sporidia mL^{-1}). Fifteen mature sori were collected from each cultivar x inoculum combination, and teliospores were cultured. After bulking 12 cultures from each cultivar x inoculum combination, the bulk culture collected from an inbred was inoculated back onto that inbred. The process was repeated for five cycles of inoculation, resulting in four cultures designated tr-5DAS, tr-5DA, Tr-5DAS, and Tr-5DA. Designation for the first isolate indicated the original culture was isolated from a *trtr* cultivar, and then cycled for five generations on Tift 23DAS. Cultures were preserved in 20% aqueous glycerine and stored at -80°C.

The virulence of cultures tr-0, Tr-0, tr-5DAS, tr-5DA, Tr-5DAS, and Tr-5DA was evaluated in three experiments in 1993. In Experiment 1, bagged panicles of Tift 23DAS and Tift 23DA were inoculated when stigmas were 50% emerged. Ten panicles of each inbred were misted with sporidial suspensions of the six cultures or a deionized water control on 18 Aug. Inoculated panicles were covered with pre-wetted plastic bags and a brown paper selfing bag. Plastic bags were removed after 18 h and selfing bags were replaced. Smut severities were estimated as the percentage of infected florets 3 weeks after inoculation. In Experiment 2, 5 mL of inoculum of the six cultures or deionized water was injected into the tips of ten boot leaves of the two inbreds as the panicles were just emerging on 23 Sep. Boot leaves were bagged after inoculation, and smut severities were estimated as above. Four cultivars were inoculated on 8 Sep in Experiment 3; the recurrent parents Tift 8677, Tift 90DBE (Hanna 1993), and corresponding trichomeless backcross$_2$, F_3 progeny. Eight panicles of each genotype were inoculated and evaluated as in Experiment 2. Severities were analyzed within each inbred x inoculation date combination, and separated by Fisher's LSD.

Smut severities of panicles inoculated with tr-0 did not differ from the control (Table 1 and 2). When retrieved from cryogenic storage, this culture resembled a single sporidial isolate with low pathogenicity (Wilson and Bondari 1990). Although virulence changes of the cultures from cycle 0 to cycle 5 could not be compared because of the anomalous characteristics of tr-0, there were no differences in final virulence among cultures repeatedly inoculated on, and isolated from, either the *TrTr* or *trtr* genotype. Selection for increased virulence to *trtr* pearl millet did not occur in these experiments. Sample sizes and genetic diversity of the original and

Table 1. Smut severities of Tift 23DAS (*trtr*) and Tift 23DA (*TrTr*) inoculated in the field with six cultures of *Moesziomyces penicillariae*.

	Experiment 1		Experiment 2	
	Tift 23DAS	Tift 23DA	Tift 23DAS	Tift 23DA
Tr-0	37.8 b[1]	72.4 ab	5.7 ab	29.4 a
tr-0	9.7 c	56.2 bc	0.3 c	4.3 b
Tr-5DAS	50.4 a	66.8 ab	4.2 ab	25.7 a
tr-5DAS	49.6 ab	78.1 a	4.0 ab	35.7 a
Tr-5DA	55.0 a	78.8 a	6.7 a	29.0 a
tr-5DA	45.4 ab	78.3 a	2.8 bc	33.6 a
Control	17.1c	46.2 c	0.0 c	0.1 b
LSD (0.05)	15.6	19.5	9.8	13.4

1. Numbers within a column followed by the same letter do not differ significantly.

Table 2. Smut severities of inbreds near isogenic at the *Tr* allele inoculated in the held with six cultures of *Moesziomyces penicillariae* (Experiment 3).

	Tift 8677		Tift 90DBE	
	(*trtr*)	*(TrTr)*	*(trtr)*	*(TrTr)*
Tr-0	10.0 a[1]	31.1 a	16.1 a	46.3 a
tr-0	0.0 c	0.2 c	0.0 c	0.4 b
Tr-5DAS	5.5 ab	21.1 ab	10.9 ab	49.4 a
tr-5DAS	1.6 bc	9.2 bc	5.5 bc	46.6 a
Tr-5DA	1.7 bc	12.9 bc	8.1 b	46.3 a
tr-5DA	3.4 be	24.5 ab	8.4 b	40.5 a
Control	0.0 c	1.1 c	0.0 c	0.1 b
LSD (0.05)	4.5	15.7	6.2	11.7

1. Numbers within a column followed by the same letter do not differ significantly.

subsequently selected cultures may be too limited to draw conclusions about long-term selection for virulence. The durability of resistance conferred by the *tr* allele will be determined only by imposing selection pressure on the pathogen population by extensive cultivation of a trichomeless hybrid.

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Evaluation of Environments in Finger Millet Genotypes

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Breeding cultivars that are adapted to a reasonably large geographical area with some degree of stability from year to year, has been a major problem confronting plant breeders. The only effective control might be to reduce environments by grouping them on the basis of their similar responses, and subsequently evaluating genotypes in representative environments from each group. This would facilitate the development of widely adopted genotypes in the selected environments with a high degree of diversity (Campbell and Lafever 1977).

In the present study, 48 genotypes of finger millet (*Eleusine coracana* (L.) Gaertn.) of diverse origin were grown in 1992 in a randomized complete block trial with three replications in six environments under irrigated black soil situations. The six selected environments represented four locations within a 500-km radius in Tamil Nadu. The environments were chosen to provide differences in rainfall, seasonal temperature, and relative humidity, representing the cultivated areas within the regions considered. Ten plants chosen at random in each genotype per replication were tagged. Observations were recorded on tagged individual plants for grain yield. The constant grain mass of hand-threshed, sun-dried panicles from each plant was recorded. Significant differences existed among the 48 genotypes for grain yield. Individual environmental effects were also highly significant for all the traits studied, indicating the differential effects of each environment.

The correlation between pairs in six environments calculated from the grain yield performance of 48 genotypes in each environment is presented in Table 1. The environment E5 (rainy season 1992, Srivilliputhur, Tamil Nadu) showed significant correlation with all other environments except E6; this would imply that E5 was a desirable environment for selecting genotypes with general adaptation. Campbell and Lafever (1977) worked out the same type of interrelationship between selected environments for grain yield in soft red winter wheat and identi-

Table 1. Correlations between pairs in six test environments calculated from the performance of 48 genotypes in each environment.

Environment	Environment					
	E1	E2	E3	E4	E5	E6
E1						
E2	0.513**					
E3	0.254	0.185				
E4	0.624**	0.230	0.247			
E5	0.510**	0.380**	0.637**	0.406**		
E6	0.261	0.169	-0.173	0.354**	0.173	

** = Significant at $P \leq 0.05$.

Table 2. Composition of cluster, and cluster means for environments over grain yield per panicle.

Group/ cluster	Environment	Cluster mean yield (g)
1	E2-Summer 1992 Killikulam E3 - Rainy season 1992 Killikulam E4 - Postrainy season 1992 Killikulam E5 - Rainy season 1992 Srivilliputhur	10.83
II	E1 -Rainy season 1992 Coimbatore	14.80
III	E6 - Rainy season 1992 Madurai	13.30

fied desirable location for selecting genotypes with general adaptation.

On the other hand, the results of the cluster analysis (Wishart 1969) for six environments over grain yield of 48 genotypes are summarized in Table 2. The composition of clusters and the relative cluster mean for six environments are also presented. The first stage of clustering E2, E3, E4, and E5 showed a high degree of similarity. As a result, if wide adaptability was desired and the resources allowed the use of six environments, E5 (rainy season 1992, Srivilliputhur, Tamil Nadu) is a representative environment from cluster I as it recorded strong yield relationship with all other environments. E1 (rainy season 1992, Coimbatore) and E6 (rainy season 1992, Madurai) from the remaining two clusters might also provide enough environmental diversity for selection of desirable stable, finger millet genotypes.

Prior evaluation of environments through yield correlation followed by cluster analysis might help any breeding program to select diversified environments in a large geographical area. This in turn could reduce the burden of conducting trials at several locations to assess the stable performance of genotypes.

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Contribution of Weather Variables to G x E Interaction in Finger Millet Genotypes

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Identification of the weather variables that contribute most to crop genotype x environment (G x E) interactions could help breeders to understand the pattern of these interactions. Little information exists on how weather variables can effect G x E interactions. Saeed and Francis (1984) found that rainfall and temperature were the most important factors involved. Gorman et al. (1989) reported that the rainfall contribution to G x E interactions was comparatively high in grain sorghum.

A common way to analyze the stability of genotypes was the regression of the trait of interest on the environmental index as defined by Freeman in 1973. It has also been suggested that the use of physical measurements of the environments could be used to explain G x E interactions (Freeman and Perkins 1971). Environmental factors might be used as covariates to remove heterogeneity (nonadditivity) from the interactions (Shukla 1972).

The present investigation estimated the contribution to the G x E interaction of grain yield, of the environmental index (Y_j = mean yield of all the genotypes in the jth environment minus the overall mean), minimum temperature, maximum temperature, preseason rainfall, rainfall during the season, and relative humidity. Six environments representing four locations and three seasons at one location within a 500-km radius of Tamil Nadu, where 48 finger millet (*Eleusine coracana* (L.) Gaertn.) genotypes grown during 1992 were used in this study (Table 1). The G x E interaction was significant for the 48 genotypes and six diverse environments. Weather variables (covariates) were used to remove heterogeneity from the interaction. The proportional contribution of weather parameters to the total G x E interactions for grain yield over environments is presented in Table 2. Of the five important weather parameters, the contributions by relative humidity followed by rainfall contributed more heterogeneity to the G x E sums of squares than any other weather variable for the finger millet genotypes studied.

Table 1. Characteristic features of six finger millet environments in Tamil Nadu, India.

Location	Season and date	Weather parameters				
		Temperature (°C)		Preseason rainfall (mm)	Rainfall (mm)	Relative humidity (%)
		Minimum	Maximum			
Millet Breeding Station, Tamil Nadu Agricultural University, Coimbatore	Rainy season (Jul-Oct 1992)	21.85	31.33	150.70	345.50	84.50
Agricultural College and Research Institute, Killikulam	Summer (Feb-May 1992)	24.06	34.59	280.60	55.70	78.23
Agricultural College and Research Institute, Killikulam	Rainy season (Jul-Oct) 1992	22.93	31.03	55.70	380.30	77.09
Agricultural College and Research Institute, Killikulam	Postrainy season (Dec 1991-Mar 1992)	21.45	27.09	515.50	146.50	79.62
Cotton Research Station, Srivilliputhur	Rainy season (Jul 1991-Oct 1992)	22.65	34.83	146.80	200.50	80.50
Agricultural College and Research Institute, Madurai	Rainy season (Jul-Oct 1992)	25.06	33.79	157.20	408.80	75.33

Table 2. Test of heterogeneity removed from G x E interaction via each of six weather covariates in finger millet.

Source of variation	df	Mean square covariates					
		Environmental index	Minimum temperature	Maximum temperature	Pre-season rainfall	Rainfall	Relative humidity
G x E	235	7.540**[1]	7.540**	7.540**	7.540**	7.540**	7.540**
Heterogeneity	47	10.570**	0.013	0.003	0.007	0.059	0.082
Residual	188	6.640**	9.421**	9.424**	9.423**	9.413**	9.400**
Pooled error	576	0.650	0.650	0.650	0.650	0.650	0.650

1. ** = significant at 0.01 level of probability.

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An Evaluation of *Setaria* Genotypes for High Temperature Tolerance

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In India foxtail millet (*Setaria italica* (L.) Beauv.), locally know as *kangni* is confined to hill slopes and undulating fields with saline and gravelly soils in Rajasthan, where it still provides assured harvests of reasonable levels under marginal cultivation by tribal or small-scale farmers. Behl (1990) proposed a method of evaluating plants for their high temperature tolerance in terms of a Germination Stress Index (GSI). This is a ratio of the promptness index of stressed seed to the promptness index of the control, expressed as a percentage. The higher the GSI, the higher the tolerance to high temperatures.

A preliminary study of 40 diverse varieties/strains of *Setaria* for high temperature tolerance was made by germinating 20 seeds of each genotype in petri dishes lined with filter paper. These were irrigated with a solution of polyethylene glycol (PEG) at the rate of 75 mL of PEG 606 to 1 L of nutrient solution. The experiment was replicated three times, and a control was grown simultaneously. The method suggested by Burton (1952) was used to compute phenotypic variance (PCV) and genotypic variance (GCV), while genetic advance as a percentage of mean genetic gain was calculated according to Johnson et al. (1955). Heritability in broad sense was estimated using Lush's formula (1940).

Analysis of variance showed that the material had sufficient variation for GSI. Based on their GSI values the genotypes were classified into three categories: tolerant, moderately tolerant, and sensitive (Table 1). Entries SIA 2592 and SIA 2607 gave the highest values of GSI, and show maximum tolerance to high temperature. Other varieties (GPUS 18, PRK 1, Arjuna, SIC 24, AK 132-1) also exhibited tolerance. These varieties could be used in further studies to develop high temperature tolerant genotypes of foxtail millet. Entries SC 21-7 and SIA 2619 were highly sensitive to high temperature.

Table 1. Classification of foxtail millet (*Setaria italica*) varieties for drought tolerance based on Germination Stress Index (GSI) values.

Tolerant (77-82%)	Moderately tolerant (70-76%)	Sensitive (63-69%)
SIA 2607	S 130	RSC 60
SIA 2592	Local	ATPS 86
GPUS 18	Vno 1	TNAU 93
PRK 1	SIA 2579	SIA 2617
Arjuna	PMS-1	SIA 2594
SIC 24	GPUS 14	SIA 2571
AK 132-1	SIA 2598	TNAU 83
GPUS	SIA 326	SIA 1616
SIA 2611	Chitra	SIA 2601
SIA 2612	Vno 3	SIA 2593
TNAU 57	V no 25	ATPS 83
GPUS 2	V no 28	Rau 12
ISC 247	SIA 2276	SIA 2619
-	-	SC 21-1

Table 2. Variability parameters for Germination Stress Index (GSI) in foxtail millet (*Setaria italica*).

Grand mean (%)	72.92
SE±	±2.17
Range	63.33-81.67
CV (%)	3.65
GCV (%)	7.38
PCV (%)	8.23
Broad-sense heritability (%)	80.4
Estimated genetic gain (%)	13.6

The GSI recorded almost equal GCV and PCV estimates. Heritability was high (80.4%) indicating the limited effect of environment on phenotype for this character. Estimates of genetic gain were 13.6%. Based on this study, considering GSI as a parameter of drought/high temperature tolerance; selection, followed by a multinational evaluation program is proposed as a methodology for identifying superior lines. Other parameters of drought tolerance should also be considered during the process.

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An Evaluation of *Setaria italica* for Seed Iron Content

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Foxtail millet (*Setaria italica* (L.) Beauv.) is grown in southern Rajasthan for food and fodder by tribal and small-scale farmers who are very poor. The crop provides assured harvests under marginal cultivation. The grain, an inexpensive poultry feed (Maloo 1992 and 1995), is particularly low in phytic acid and rich in iron and calcium (Sampath et al. 1990). Because of its nutritional importance, seed of 40 diverse varieties/strains of foxtail millet were evaluated for their iron content. The material was sown during the 1993 rainy season at Rajasthan College of Agriculture, Udaipur. Each variety was sown in a 3-m long row at a spacing of 25 x 8 cm. The experiment was conducted in a randomized block design with three replications. Seed iron content was estimated calorimetrically by the method of Chapman and Pratt (1961). The method suggested by Burton (1952) was used to compute phenotypic variance (PCV) and genotypic variance (GCV) while the genetic advance as a percentage of the mean genetic grain was calculated according to Johnson et al. (1955). Heritability in the broad sense was estimated using the formula of Lush (1940).

Analysis of variance showed that the genotypes differed significantly. The varieties/strains were classified into high, moderate, and low iron content categories (Table 1). GPUS 14, GPUS 18, and S 130 had the highest iron content (0.11%) followed by SIA 2619, ATPS 83, ISC 247, SIA 326, and the Local. These genotypes could be used in a breeding program for this character.

Seed iron content exhibited moderately high GCV (24.77%), heritability (89.42%), and genetic gain (48.25%) (Table 2) which suggested the predominance of additive gene effects. Therefore, selection for high seed iron content would be effective.

Table 1. Classification of foxtail millet varieties/ strains on the basis of seed iron content.

High iron content (0.09-0.11%)	Moderate iron content (0.07-0.08%)	Low iron content (0.05-0.06%)
GPUS 14	SIA 2579	V no. 1
GPUS 18	PRK 1	Chitra
S 130	SC 21-1	GPUS 2
SIA 2619	SIA 2276	Rau 12
ATPS 83	SIA 2611	SIA 2612
ISC 247	SIA 1616	SIA 2601
Local	TNAU 57	SIA 2593
SIA 326	ATPS 86	SIA 2592
SIA 2599	Arjuna	PMS - 1
TNAU 43	RSC 60	SIA 2571
V no. 25	SIA 2607	SIC 24
V no. 28	AK 132-1	TNAU 83
-	V no. 3	SIA 2617
-	-	SIA 2598
-	-	GPUS 17

Table 2. Variability parameters for seed iron content in foxtail millet.

Grand mean (%)	0.07
SE	±0.01
Range	0.05-0.11
CV(%)	8.52
GCV(%)	24.7
PCV (%)	26.2
Heritability (%)	89.4
Genetic gain (%)	48.2

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Pathology

Pearl Millet as an Alternate Host of the Sorghum Ergot Pathogen, *Claviceps africana*

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Introduction

The ergot pathogen, *Claviceps africana* Frederickson, Mantle and de Milliano, has been the major cause of severely depleted yields in sorghum (*Sorghum bicolor* (L.) Moench) hybrid seed production in southern Africa (de Milliano 1992). In Zimbabwe the pathogen causes annual grain losses of up to 25% following the colonization of male-sterile A-line ovaries, and additional losses of up to 12% also occur when contamination of seeds with honeydew causes mold growth, spoilage, and quality reduction (Frederickson and Leuschner, in press, McLaren 1994).

The host range of *C. africana* is poorly defined. In some of the earlier experiments with *C. africana* by Futrell and Webster in Nigeria in 1966, natural inoculum from *Panicum maximum* infected sorghum. Similarly, ergot from the same grass in Thailand was transferred experimentally to sorghum, as was inoculum from *Dicanthum annulatum, Brachiaria mutica,* and three sorghum species, *S. sudanensis, S. almum,* and *S. halcpanse* (Boon-Long 1992). It is assumed, from the evidence on sorghum ergot in Thailand (Frederickson et al. 1991), that the findings of Boon-Long all refer to *C. africana.* However, *C. africana* has not been found on any alternate host outside the genus *Sorghum* in Zimbabwe. Further, that the Indian sorghum ergot pathogen (*C. sorghi,* anamorph *Sphacelia sorghi)* can also infect *Jschaemum pilosum, Cenchrus setigerous,* and *C. ciliaris* (Chinnadurai and Govindaswamy 1971, Mughogho 1986) is not necessarily relevant to vegetative hyphal parasitism by *C. africana* since the two sorghum pathogens are taxonomically distinct, and *C. ciliaris* could not be infected by sorghum ergot in Zimbabwe, even using a high concentration of inoculum.

In Zimbabwe, pearl millet (*Pennisetum glaucum* (L.) R. Br.) is grown alongside sorghum as a communal crop. Although it matures earlier than sorghum, extensive tillering causes temporal overlap of the two crops. Since Sundaram (1974) found sphacelial infections of *C. sorghi* on pearl millet adjacent to sorghum in India, we thought that infectivity of *C. africana* on pearl millet should be studied experimentally in Africa.

Materials and Methods

At Matopos Research Station, near Bulawayo, Zimbabwe, pearl millet lines were sown in a 4 m x 6 m block in six replications in 1991, and two replications in 1992. Due to seed availability only four lines were common to both years. Upon emergence from the boot in April, spikes were bagged and inspected daily for the onset of stigma emergence. At approximately 20% stigma emergence they were inoculated with either the natural pathogen, *C. fusiformis,* or the sorghum ergot pathogen *C. africana,* Conidial inoculum (106 conidia mL^{-1}) was directed at inflorescences until run-off. Spikes were re-bagged, and the inoculation procedure repeated over the next 2-3 days until the completion of stigma exsertion. Concurrent inoculations of A-line sorghum with *C. africana* were performed to verify the infectivity of *C. africana* inoculum.

Ergot incidence and severity were assessed on pearl millet spikes 3-4 weeks post-inoculation. Infected spikes were removed to encourage further tillering of the millet and to allow microscopal verification of the identity of the pathogen based on conidial characteristics. In 1991, *C. africana* inoculum from successful pearl millet infection was re-inoculated onto pearl millet to see if its infectivity changed after one passage through the host.

Results

Claviceps africana consistently gave 100% disease incidence on male-sterile sorghum, and in the absence of a

Table 1. Comparative experimental ergot disease incidence in pearl millet genotypes by the natural pathogen, *Claviceps fusiformis,* and the unnatural pathogen, *Claviceps africana,* in Zimbabwe, 1991 and 1992.

	Disease incidence (%)			
	Natural pathogen *C.* fusiformis	Unnatural pathogen C. africana		*C.* africana after passage through pearl millet
Pearl millet line	1991	1991	1992	1991
ICMPES 25	-[1]	-	3	-
ICMPES 35	-	-	11.5(70)	-
ICMPES 39	0(12)[2]	15(138)	10	2(47)
ICMPES 45	23(13)	16(124)	4	3(54)
ICMSR 221	14(14)	17(218)	-	2(74)
ICMSR 260	43 (15)	23 (167)	-	7(77)
ICMH 451	0(10)	7 (62)	-	4(23)
PMV 1	36(11)	20(183)	18(114)	11 (65)
852 B	7(67)	2.5(78)	7 (14)	-

1. - = not tested.
2. Number of inoculated inflorescences shown in parentheses.

pollinator, achieved approximately 95% disease severity within infected inflorescences.

The natural ergot pathogen of pearl millet (*Claviceps fusiformis*) established disease with moderate incidence on most, but not on all, of the lines tested (Table 1); but disease severity was relatively low, not exceeding 15%.

In contrast, *C. africana* established a parasitic association with all the pearl millet lines tested, with incidence as high as 23% in ICMSR 260, the genotype that had also supported the highest incidence when inoculated with *C. fusiformis.* However, severities were always low, at 1-5%. Consistent findings were obtained in the pearl millet lines that were common to the 2 consecutive years' experiments. Arc-sine transformed data for experiments in 1992 showed the mean comparative incidence of *Claviceps africana* in a sorghum A-line (100 %) versus three pearl millet lines (2.5,11.5, and 18%) were significantly different at $P = 0.01$. All infections on pearl millet lines were verified as the sphacelial stage (*Sphacelia sorghi*) of *C. africana* microscopically by virtue of their conidial characteristics; the sphacelial fructification of *C. fusiformis* is quite different from that of *S. sorghi.*

After one passage through a pearl millet host, *C. africana,* did not apparently become more infectious on this host. Rather, the results suggest that infectivity may have declined. Indeed, although *C. africana* inoculum passaged through pearl millet still infected male-sterile sorghum, it did so with reduced (49%) severity.

Discussion

The experimental observations confirm pearl millet as an additional host of endemic *C. africana* under high disease pressure in Zimbabwe, even in the more difficult conditions for infection during years of severe drought in southern Africa. While this may not be of local practical importance, the recent global extension of ergot disease in sorghum for the first time in South America east of the Andes in 1995 (Reis et al. 1996) and in Queensland, Australia in 1996, has greatly heightened interest in and concern for the economic consequences of the disease. Relatively little firm evidence on reservoirs of inoculum exists in the literature and the present short report, coupled with similar recent findings in Brazil (E M Reis, personal communication) and Queensland (M Ryley, personal communication) formalizes a role for pearl millet that may at least be helpful in phytosanitary considerations to reduce further adverse impact of *C. africana* disease in sorghum. Whereas ergot disease principally influences F_1 hybrid seed production, the effects on grain sorghum production could become significant if widespread reservoirs of infection become established.

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Effect of Different Levels of Nitrogen and Time of Sowing on Incidence of Grain Mold in Pearl Millet

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Pearl millet, *Pennisetum glaucum* (L.) R. Br., the fourth most important food crop in India, it is a drought-tolerant crop widely distributed in the semi-arid tropics. Among several factors that restrict the production potential of pearl millet, head molds play a dominent role in reducing production, and the market value of grain in Chittoor and Cuddapah districts of Andhra Pradesh.

In preliminary studies conducted in the laboratory, several fungi, e.g., *Curvularia* spp, *Alternaria* spp, *Fusarium* spp, *Drechslera* spp, and *Penicillium* spp were found associated with head mold of pearl millet. Similar results were also reported by Luttrell (1954) in USA, and Girisham and Reddy (1985). Therefore, this study was made to determine the effect of different levels of nitrogen, and different sowings dates on the incidence of mold in pearl millet.

The seeds were sown at 10-day intervals, starting 27 Jul 1989 at a seed rate of 4 kg ha^{-1}, in a nursery that was maintained weed-free for 21 days. After fertilizers had been applied to the main field, 21-day-old healthy seedings were transplanted into it at the rate of one seedling $hill^{-1}$, with 45 cm between rows and 15 cm within the rows.

The experiment was conducted using a split-plot design with sowing dates as the main plots (18 x 13.5 m), and N levels as subplots (3.6 x 2.7 m). All the treatments were replicated thrice. The five sowing dates and five nitrogen levels used in 1989 as treatments were D_1 (27 Jul), D_2 (7 Aug), D_3 (17 Aug), D_4 (27 Aug), D_5 (7 Sep), N_0 (0 kg N ha^{-1}), N, (25 kg N ha^{-1}), N_2 (50 kg N ha^{-1}), N_3 (75 kg N ha^{-1}), N_4 (100 kg N ha^{-1}).

There were 25 treatments for various combinations of sowing dates and nitrogen levels:

T_1-D_1N_o	T_6-D_2N_0	T_{11}-D_3N_0	T_{16}-D_4N_0	T_{21}-D_5N_0
T_2-D_1N_1	T_7-D_2N_1	T_{12}-D_3N_1	T_{17}-D_4N_1	T_{22}-D_5N_1
T_3-D_1N_2	T_8-D_2N_2	T_{13}-D_3N_2	T_{18}-D_4N_2	T_{23}-D_5N_2
T_4-D_1N_3	T_9-D_2N_3	T_{14}-D_3N_3	T_{19}-D_4N_3	T_{24}-D_5N_3
T_5-D_1N_4	T_{10}-D_2N_4	T_{15}-D_3N_4	T_{20}-D_4N_4	T_{25}-D_5N_4

The results indicated that there was minimum (12.9%) mold incidence in the crop sown on 17 Aug with 0 kg N ha^{-1}. Such low incidence may be due to the prevailing high temperature (36.4°C) coupled with low (68.4%) rel-

Table 1. Effect of nitrogen levels and sowing dates on mold incidence in pearl millet, Andhra Pradesh, India, 1989.

Sowing date	Mean incidence (%) nitrogen level (kg ha^{-1}) N_0 (0)	N_1 (25)	N_2 (50)	N_3 (75)	N_4 (100)	Mean	Relative Temperature °C Max	Min	Humidity (%) Max	Min	Rainfall (mm)	(days)
27 Jul	12.10	13.30	14.40	14.80	17.20	14.30	35.70	25.50	73.89	50.90	2.48	18.00
	(3.49)	(3.66)	(3.79)	(3.81)	(4.15)	(3.79)						
7 Aug	12.30	13.40	14.30	15.30	18.50	14.70	35.10	23.60	73.80	52.80	3.44	12.00
	(4.3)	(3.67)	(3.78)	(3.92)	(4.30)	(3.84)						
17 Aug	12.00	12.50	12.60	13.50	14.20	12.90	36.41	25.20	68.60	46.50	4.23	11.00
	(3.56)	(3.58)	(3.58)	(3.68)	(3.78)	(3.56)						
27 Aug	20.40	21.16	21.12	23.10	23.30	21.30	34.10	25.80	79.80	57.20	5.32	18.00
	(4.52)	(4.65)	(4.67)	(4.81)	(4.91)	(4.13)						
7 Sep	20.70	21.60	22.60	23.30	24.10	23.30	32.10	22.60	81.25	58.76	5.85	20.00
	(4.30)	(4.60)	(4.76)	(4.83)	(4.91)	(4.73)						
Mean	15.2	15.9	16.8	17.8	19.3							
	(3.91)	(3.99)	(4.10)	(4.20)	(4.39)							

	Dates	N	Net date	Date at N
SE	±0.04	±0.02	±0.02	±0.09
CD (%)	0.10	0.04	0.09	0.19

1. Numbers in parentheses are square root transformed values.

ative humidity (RH) during the heading stage (Table 1), because high temperatures and low RH do not favor mold development. The maximum mold incidence (23.3%) was observed in the crop that was sown late, i.e., on 7 Sep with the highest dose of N (100 kg N ha^{-1}). The high mold incidence was due to the fact that crop maturity coincided with low temperatures (32.1°C) and high RH (81.2%). A high dose of nitrogen, and 20 rainy days probably proved favorable for infection and mold development. A significant decrease in mold incidence was observed when the crop was sown early, i.e., 27 Jul (14.3%) 17 Aug (14.2%), and 27 Aug (21.3%). The mean mold incidence (15.2%) was very low in the plots that did not receive nitrogen (0 kg N ha^{1}). This clearly indicates that the disease incidence will be high at high rates of nitrogen fertilizer application in similar climatic conditions. Similar findings were reported by several other workers on sorghum head molds. Denis and Girard (1978) reported that the late-sown pearl millet crop that matured during wet weather recorded maximum mold incidence.

In conclusion, the high head mold incidence in the late-sown crop was due to crop maturity coinciding with high rainfall during the northeast monsoon. The mold incidence was low with least N fertilizer, while the incidence was high at the highest level of N applied.

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Pearl Millet Disease Scenario in Southwestern Haryana

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The southwestern zone of Haryana that covers the districts of Bhiwani, Gurgaon, Mohindergarh, and Rewari

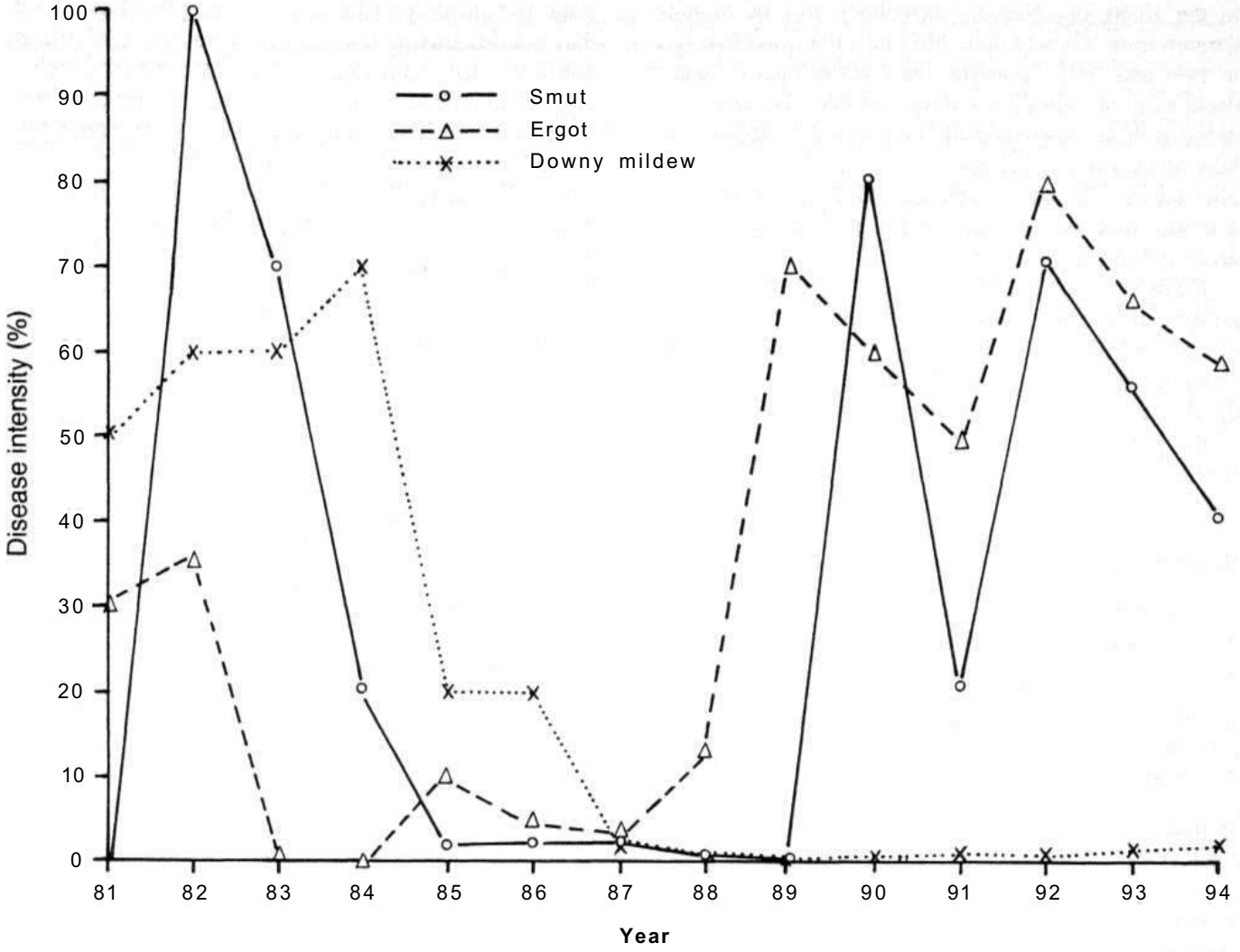

Figure 1. Pearl millet disease intensity (%) in southwestern Haryana, 1981-94.

has an extremely arid/semi-arid environment. Pearl millet (*Pennisetum glaucum* (L.) R. Br.) is the major rainy-season cereal crop. The zone was surveyed regularly from 1981 through 1994 to assess the extent of damage caused by the major pearl millet diseases.

The survey was conducted annually in the first week of Sep by purely random sampling. The occurrence and intensity of diseases was determined by counting healthy and diseased plants in a 4 m^{-2} area for each sample. Disease intensity (%) was calculated by grading the disease severity on individual pearl millet panicles using a rating scale (Williams et al. 1976).

The survey results (Fig. 1) indicated wide fluctuations in downy mildew/green ear *(Sclerospora graminicola)* disease intensity in different years. This disease caused major losses from 1981 to 1984. In 1985 and 1986, disease intensities up to 20% were recorded. However, from 1987 to date, the disease appeared sporadically either at low intensity, or in traces. This could be attributed to the severe drought and desiccating winds in 1987 which destroyed inoculum in the soil, and to the release and adoption of downy mildew tolerant/resistant hybrids.

Smut disease (*Tolyposporium penicillariae*) was recorded at 35% in 1981 and 1982. From 1983 to 1987, the disease was either observed in traces, or below 10%, but in 1989, it appeared as an epidemic with 70% to 100% intensity. From 1989 through 1994, smut gained importance, appearing regularly and severely. These observations conform with those of Rachie and Majumdar (1980) who reported that with the widespread commercial cultivation of newly developed F_1 hybrids, smut disease assumed importance in northern India.

The survey showed that ergot (*Claviceps macrocephala*) is a sporadic disease. Intensities up to 35% were recorded in Bhiwani district, and 100% infection was noted in some fields in Gurgaon district during 1981-83. Ergot intensity remained low (1-5%) during 1985-87. After 1987, the disease was absent from the zone, except

in the Kund and Nangal Chowdhury area of Mohindergarh district where up to 80% infection was observed in 1991 and 1992. However, the disease intensity there declined to 50% in 1993 and 40% in 1994. Disease incidence at these locations could be due to their location in hilly areas where high humidity prevails during the cropping season. Chahal and Dhindsa (1985) quoted ergot as a serious problem in almost all the pearl millet growing areas in India, but this was not confirmed by this study.

It can be concluded from the above results that smut is a major disease in southwestern Haryana, where downy mildew incidence is declining. Ergot disease appears sporadically in selected pockets. There is a dire need to develop ergot- and smut-resistant hybrids for this zone, as the presence of isolated pockets of heavy inoculum could cause epidemics.

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Food and Feed Quality

Use of Proso Millet Malted Flour in Low-cost Nutritious Sweets

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Proso millet (*Panicum miliaceum*) like other small millets, is a staple food of poor people, whose nutritional status is dependent on the quality of the millet-based food they eat. Malting grains improves their digestibility and nutritive value. An increase in biological value, ascorbic-acid, thiamin, riboflavin, and minerals on sprouting has been reported (Chavan and Kadam 1989). The suitability of grain malt in the diets of young children is well established (Gopaldas 1992). To date, grain-malted flour has mainly been used in food products where amylase activity is desired. The use of grain-malted flour in other products could provide highly nutritious food to whole families, including children. Malting, being a simple technique, can be done at the household level. The present study was undertaken to study the taste and acceptability of *burfi* (Indian sweets) prepared from proso millet malted flour.

Proso millet grain was obtained from the local market in Haldwani, Nainital, Uttar Pradesh. It was made into malted flour by the standard method generally followed at household level (Gopaldas 1992). An 'instant' mix containing 50% proso millet malted flour, 25% roasted green gram powder, and 25% roasted groundnut powder was prepared. Fat (5 g per 100 g mix) was rubbed into the mix. This mixture was used to prepare *burfi* with *jaggery* (raw sugar) syrup. The *burfi* was garnished with defatted coconut powder.

The estimated cost of *burfi* was Rs 21 kg^{-1} (US$0.6). The protein content was 12.3 g 100 g^{-1} and the energy content 429 kcal 100 g^{-1}. Since malted wheat flour has an acceptable taste (Malleshi 1986), and traditional sweets made from roasted wheat flour are widely acceptable, a taste comparison of malted proso millet *burfi* and two other types of *burfi* was made. In one type, malted proso millet flour was replaced by malted wheat flour, while in the other it was replaced by roasted wheat flour. These different types of *burfi* were scored by a semitrained panel of 10 members. The analysis of variance technique was used to sort out variance among characters (Snedecor and Cochran 1968).

The results showed that the three types *of burfi* did not differ significantly when scored for color, flavor, texture, appearance, and overall acceptability. The overall acceptability of all three types of *burfi* was rated as good (Table 1).

The acceptability of proso millet *burfi* to 3- or 4- year-old children was also assessed. A total of 23 children were offered the product and their reactions recorded by personal observation and interview; 86.95% of the children liked the *burfi.* This product could be particularly beneficial to families living in the hills of Uttar Pradesh, India where proso millet is consumed as a staple food, but milk and milk products are not easily available.

Table 1. Sensory quality characteristics scores[1] of different types of burfi.

Major ingredient	Color	Flavor	Texture	Appearance	Overall acceptability
Roasted wheat flour	7.6	7.0	7.0	8.0	7.6
Malted wheat flour	7.0	6.5	7.4	7.7	7.4
Malted proso millet flour	7.0	6.5	7.0	7.0	7.0
CD at 5%	1.72	1.80	1.65	1.43	1.24

1. Scored on a scale of 1-10 where 1-2 = very poor, 3-4 - poor, 5-6 - fair, 7-8 - good, 9-10 - very good.

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Notes and News

Food Technology Research in SADC Countries

During its first (1983-88) and second (1988-93) phases, the Southern African Development Community/International Crops Research Institute for the Semi-Arid Tropics (SADC/ICRISAT) Sorghum and Millet Improvement Program (SMIP) supported the postgraduate training of 10 food technologists from seven SADC countries. Two of them also received in-service training or technical support. Many of these scientists have left work in the national agricultural research systems (NARS) and are now employed in universities, industry, or industrial research and development institutions, but few work on sorghum and pearl millet.

SMIP's investment in food technology research has, however, been reduced during its third phase (1993-98), and now emphasis is only on the grain quality screening aspects of related work. The viability of food technology programs in NARS institutions remained unknown, and the loss of food technologists from these programs suggested the need to reassess the comparative advantage of such programs and to identify the requirements for their sustainability. Additionally, it was recognized that further investment in NARS programs needs to be more directly related to the comparative advantage bestowed by the employment of food technologists in NARS institutions relative to their colleagues in universities, industrial research organizations, and food-processing industry.

It was against this background that the SMIP Steering Committee recommended a study to assess the working environment of each SMIP-trained food technologist in the SADC region, including their facilities for research and other activities, funding availability, and national priority of sorghum and pearl millet utilization in order to facilitate the active participation of the technologists in sorghum and pearl millet utilization work. A workshop to discuss the study report and agree a strategy of in-country and regional sorghum and pearl millet utilization was also recommended, and held in Harare, 29-30 Jan 1996.

Workshop agenda

- Present and discuss the study report- an analytical synthesis of country reports from the eight participating SADC countries. Discuss specific aspects of the report with emphasis on issues focussing on needs, constraints, and opportunities.
- To identify and recommended future action on each of those specific issues, and develop an action plan.

Workshop recommendations

- A network of SMIP-trained food technologists should be formed to facilitate information and staff exchange programs within and outside the SADC region, and to strengthen collaborative research work. Members should meet every year to review their activities.
- Each NARS in the SADC region should issue a policy statement on food technology.
- Food technology facilities/equipment should be improved within NARS, and the Southern African Centre for Cooperation in Agricultural and Natural Resources Research and Training (SACCAR) should seek the necessary funding.
- Industry and SACCAR should collaborate in food technology research.
- Specialized training in food technology and in technology transfer should continue on the job.
- Breeders and food technologists should establish meaningful linkages.

Recommendations by participants from industry

- SACCAR should include industry representatives in its membership, or its deliberations should receive input from industry.
- The University of Zimbabwe and the Department of Research and Specialist Services should seriously consider collaborating with the industry, and pooling resources and facilities. They could also link with other universities and institutions in the region and lead in the training of food scientists and technologists and the coordination of research at basic and applied levels, including rural development.
- Food technology research on sorghum, millets, and other cereals should primarily be market-oriented. Industry should provide the necessary guidance.

A Report on the survey, and the workshop proceedings can be obtained from ICRISAT Southern and Eastern Africa Region, P O Box 776, Bulawayo, Zimbabwe:

Oniang'o, R.K. 1996. Sorghum and pearl millet food technology in SADC countries: a report of a study for the SADC/ICRISAT Sorghum and Millet Improvement Program (SMIP). Bulawayo, Zimbabwe: ICRISAT Southern and Eastern Africa Region. [Limited distribution.]

Obilana, A.B. (ed.) 1996. Sorghum and pearl millet food technology in SADC countries: proceedings of a Regional Workshop, 29-30 Jan 1996, Harare, Zimbabwe. Bulawayo, Zimbabwe: ICRISAT Southern and Eastern Africa Region. [Limited distribution.]

First Pearl Millet Topcross Release in India

The first officially recognized release in India of a pearl millet topcross hybrid, was announced recently by government authorities in the Indian State of Madhya Pradesh.

The hybrid, named 'Jawahar Bajra Hybrid 1 (JBH 1)', was developed by pearl millet breeders at ICRISAT Asia Center (IAC), Patanchcru, and the JNKVV College of Agriculture in Gwalior. After 3 years of testing in national trials (as GICH 91834 = MH 501), and state-level, on-farm testing, the release proposal was accepted by the State Varietal Release Committee at its late August meeting in Bhopal, Madhya Pradesh.

JBH 1 seed is produced by crossing a topcross pollinator population, ICMR 501 = PRLBSC TCP 1, onto the widely used cytoplasmic male-sterile line ICMA 1 = 81A. Both parents were developed at IAC. This topcross hybrid has high grain yield potential (2.0-2.6 t ha^{-1}) that is competitive with the best available single-cross hybrids of comparable maturity (80-85 days from emergence to harvest). The hybrid plants are of moderate height (1.5-2.0 m), they have medium long (20-25 cm) nonbristled compact panicles, and medium-bold, globular grain (1000-grain mass 11 g).

Both the hybrid and its topcross pollinator are highly resistant to pearl millet downy mildew disease. The pollinator, ICMR 501, was bred by mass selection following random mating of 11 phenotypically similar, early flowering, downy mildew resistant inbred restorer lines developed from the ICRISAT Bold Seeded Early Composite. As its population pollinator is not genetically uniform for its downy mildew resistance, it is expected that widespread repeated cultivation of JBH 1 should not cause the rapid changes in pathogen virulence observed in the past when popular, genetically uniform single-cross hybrids HB 3, BJ 104, MBH 110, and MLBH 104 succumbed to epidemics following host-directed evolution of new downy mildew strains.

The official release of this new hybrid type could thus be a major breakthrough in the continuing battle against pearl millet downy mildew, the major biotic constraint to pearl millet production in India.

Network News

A Research and Network Strategy for Sustainable Sorghum Production Systems for Latin America: an Inter Center Initiative

Belum V S Reddy[1] and R Raul Vera[2] (1. Genetic Enhancement Division, ICRISAT Asia Region, ICRISAT Asia Center, Patancheru 502 324, India. 2. Lowland Tropical Production Systems Program, Centro International de Agricultura Tropical (CIAT), Cali, Colombia)

Vast areas of plains (generally called savannas, llanos or cerrados) in Colombia, Brazil, Venezuela, and Bolivia in Latin America are traditionally used for extensive livestock production. The soils are acidic; Al^{+3} saturation ranges from 0% near the mountains to 90% at a distance of 200 km. For many areas, the rainfall follows a bimodal distribution with August being dry. Research at CIAT has contributed to the replacement of native grasses by *Brachiaria* spp. There is growing awareness among farmers of opportunities to raise productivity and diversify these pastoral systems with crops. CIAT is experimenting with various alternative systems involving rainfed upland rice in mixed systems. Availability of high-yielding sorghums adapted to these savannas/cerrados will contribute further to the diversification of the farming systems of the region.

There has been active interaction between ICRISAT, CIAT, INTSORMIL, and the national systems of the region in developing a program of sorghum genetic improvement to complement the CIAT-led ecoregional initiative for the acid-soil savannas. These included a proposal in 1993/4 by ICRISAT/INTSORMIL/CIAT to the Inter-Amcrican Development Board (IDB), and a modified proposal by CIAT/ICRISAT in 1995. The result has been a project of reduced scale in 1996/97, funded by a $250,000 grant by IDB.

The basic thrust of this project is to establish and strengthen a basic infrastructure for sorghum genetic improvement in the region. The three main objectives are the transfer of sorghum genetic resources to the region, initiation of sorghum improvement in the region, and training of national scientists. Specific objectives include:

- assemble and multiply agronomically elite sources of sorghums with acid-soil tolerance and foliar disease resistance, and evaluate these sorghums across a number of environments relevant to the acid-soil savannas of Latin America;

- identify and develop high-yielding seed parents, open-pollinated varieties, and restorer lines with tolerance to acid soils and low phosphorous availability combined with resistance to foliar diseases (principally anthracnose and gray leaf spot) by evaluating breeding products in a systems context;

- develop an effective network for the evaluation of progenies, sharing of information, data and materials, and enhancement of knowledge on sorghum improvement for the region through workshops and training courses. A range of pearl millet genetic materials will also be transferred to the region.

A range of 777 sorghum restorer lines and 378 maintainer lines bred for their high-yielding ability, resistance to shoot fly, stem borer, grain mold, anthracnose, leaf blight, and rust, staygreen trait, and for forage, with tillering ability were introduced into Colombia from ICRISAT in late 1995. Two broad-based populations (large grain population and high tillering population) with a genetic male-sterile gene and eight leaf disease resistant/susceptible or high-yielding control lines were also introduced.

The materials were multiplied and evaluated at CIAT, Palmira, Colombia for rust resistance and high yield during Dec 1995-Apr 1996. Two hundred and sixty-nine restorer lines (grain), 33 forage lines, and 228 B-lines were selected for further evaluation under acid-soil conditions. These materials are being evaluated in replicated trials at Quilichao (in collaboration with CIAT) and La Libertad (in collaboration with CORPOICA, Colombia) at different acid-soil ($Al+^{3}$ saturations 40% at Quilichao and 60% at La Libertad) conditions during the May-Aug season 1996.

Selections from the May-Aug season selection trials will be evaluated in the following season for their productivity under acid soil conditions. The resulting lines, after multiplication, will be distributed and tested through the network with the national programs (Colombia, Venezuela, Bolivia, and Brazil) in the region. Further, six scientists from the region will interact with ICRISAT scientists at IAC, India in 1996 and 1997, with a particular focus on genetic improvement of sorghum and pearl millet. The current IDB-funded project will result in the establishment of a significant infrastructure in the region for sorghum and pearl millet improvement. The potential for further research by ICRISAT is uncertain, because sorghum improvement is not a component of the CIAT-led ecoregional program focussed on the savanna ecosystems. However, ICRISAT will remain eager to spillover into the region all relevant knowledge, technologies, and materials from its work in other regions.

Cereals and Legumes Asia Network

The Cereals and Legumes Asia Network (CLAN) was established in 1992 by merging the erstwhile Asian Grain Legumes Network (AGLN) and the Asian component of Cooperative Cereals Research Network (CCRN).

CLAN is a network of scientists who work together to alleviate production constraints for increased and sustained production of sorghum, pearl millet, chickpea, pigeonpea, and groundnut in Asia.

Sorghum is an important crop in China, India, Indonesia, Iran, Myanmar, Pakistan, Philippines, and Thailand. Pearl millet is widely grown in India and Pakistan.

CLAN objectives

- Strengthen linkages and enhance exchange of germplasm, breeding material, technical information, and technology options among members;

- Facilitate collaborative research among members to address high-priority production constraints with particular focus on poverty and equity issues;

- Assist in improving the research and extension capability of member countries through human resource development;

- Enhance coordination of regional research on sorghum, millets, chickpea, pigeonpea, and groundnut;

- Contribute to the development of stable and sustainable production systems through a responsive research capability in member countries.

Membership

CLAN activities are in progress in Bangladesh, China, India, Indonesia, Myanmar, Nepal, Pakistan, Philippines, Sri Lanka, Thailand, and Vietnam. All scientists and administrators working in regional or international institutions in Asia and interested in CLAN priority crops are invited to become cooperators in the network. A directory of network cooperators is available with all cooperators.

CLAN Coordination Unit

The Coordination Unit (CU) is based at ICRISAT Asia Center, Patancheru 502 324, Andhra Pradesh, India. The CU provides logistic and administrative support to network activities. Guidelines for network activities are provided by a Steering Committee of Country Coordinators, and a CLAN Advisory Committee. The CLAN Coordinator facilitates the implementation of planned activities.

Country Coordinators

Each member country nominates a Country Coordinator, who is responsible for the coordination and liaison of in-country collaborative research for the network. The Country Coordinator is the main administrative link between the CLAN-CU and the national program.

Network activities

CLAN supports diverse activities depending on the needs, interests, and capabilities of member countries. Some of the activities are:

- Exchange, testing, and use of germplasm and breeding material in national programs (as released varieties, or as parents in breeding programs).
- Support to specialized Working Groups (or subnetworks) to undertake research on such specific, high-priority regional constraints to production as drought tolerance in sorghum; shoot pests of sorghum; forage sorghums; grain mold, etc.
- Bilateral collaborative research specific to Asia, between national programs and ICRISAT, or between a mentor institution and ICRISAT.
- Assistance in identifying training needs, organizing special training courses, in-country training programs, and organizing workshops and meetings to meet the specific needs of Asian researchers,
- Exchange of information as proceedings of workshops and meetings, research bulletins, information bulletins, and newsletters.

In brief, CLAN aims to contribute to strengthening national programs by helping focus efforts on the priority needs and opportunities of member countries, and through closer collaboration with regional and international institutions in Asia with common goals and objectives. CLAN also aims to help better target available resources and funds, and minimize overlap and duplication of research effort.

Millet Research Network

The West and Central Africa Millet Research Network (WCAMRN), better known by its French acronym, ROCAFREMI, aims to strengthen and contribute to research on millet within the National Agricultural Research Systems (NARS) in the Western and Central Africa region and to enhance food security at the household level. At present, 14 countries participate in the network: Benin, Burkina Faso, Cameroon, Chad, Cote d'Ivoire, Gambia, Ghana, Guinea-Buissau, Mali, Mauritania, Niger, Nigeria, Togo, and Senegal.

The ROCAFREMI program focuses on millet research, production, and natural resource management in millet-based cropping systems of semi-arid western and central Africa. Research areas include: 1. identification and/or development of improved millet varieties; 2. study of the bioecology of millet insect pests and development of appropriate control measures; 3. improvement of downy mildew control measures; and 4. improvement of millet-based cropping systems.

ROCAFREMI intends to provide fellowships for African students to conduct their thesis research within these on-going activities. The program also organizes training sessions for NARS scientists involved in the activities of the network. Monitoring tours are organized each year during the cropping season to evaluate on-station and on-farm trials and experiments conducted by member countries. Monitoring tours also provide opportunities for 'on-the-spot-training' in the various countries. ROCAFREMI is funded by the Swiss Agency for Development and Cooperation (SDC).

For more information contact the Network Coordinator, Dr Botorou Ouendeba, ICRISAT Sahelian Center, B P 12404, Niamey, Niger (via Paris).

Sorghum Research Network

The West and Central Africa Sorghum Research Network (WCASRN), or ROCARS in French has the mandate of increasing sorghum productivity through regional collaborative research activities in 17 sorghum-producing countries in Western and Central Africa: Benin, Burkina Faso, Cameroon, Cape Verde, Central African Republic, Chad, Cote d'Ivoire, the Gambia, Ghana, Guinea-Bissau, Guinea Conakry, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, and Togo.

The major activities of the network are varietal testing, seed multiplication and exchange, monitoring tours, training and workshops. A coordinator oversees research in member countries through national coordinators in addition to the conduct of resident research. The Network is funded by the United States Agency for International Development (USAID).

For more information contact the new Network Coordinator, Dr Inoussa Akintayo, who is presently working in N'Djamena, Chad, in an FAO/UNDP project. Dr Akintayo can be contacted at ICRISAT Western and Central Africa Region, B P 320, Bamako, Mali.

Forthcoming Conference and Workshop

Global Conference on Sorghum Ergot, 2-7 Jun 1997, Sete Lagoas, Minas Gerais, Brazil

The Empresa Brasileira de Pesquisa Agropecuaria (EMBRAPA)/Centro Nacional de Pesquisa de Milho e Sorgo (CNPMS) is organizing a Global Conference on Sorghum Ergot, 2-7 Jun 1997, at the CNPMS Center in Sete Lagoas, Minas Gerais, Brazil (35 km from the Belo Horizonte Airport). The proposed program includes:

- overviews (enhanced geographic distribution of ergot, its causes and implications; sorghum ergot in Brazil; status of sorghum production in Brazil; seed production methods)
- regional presentations (Southern Africa, India, South America, Australia, USA, etc.)
- diagnostics and disease epidemiology (host-pathogen-environment interaction, DNA comparisons and alkaloid production, pathogen survival, spread, and disease cycle)
- ergot management strategies (quarantine, host-plant resistance, cultivar control, chemical control, seed processing, integrated ergot management)
- future needs and strategies, and international collaboration
- technical excursion (6-8 Jun 1997) to CNPMS/EMBRAPA research plots and visits to private-sector seed production fields.

The conference is being sponsored by EMBRAPA, INTSORMIL, and ICRISAT; additional sponsors are also being considered. The official language of the conference will be English, with one or two presentations in Portuguese. For further information, contact:

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Regional Workshop on Soil Fertility Management in West African Land Use Systems 4-8 Mar 1997, Niamey Niger

Soil fertility in most of the traditional land-use systems in western Africa is rapidly decreasing, accompanied by a sharp fall in per capita food production. As population continues to grow and land for crops and grazing becomes increasingly scarce, new strategies are required to assist rural populations in sustaining their natural resources. Technological innovations for the improvement of soil fertility need to be backed up by institutional and political arrangements in order to tackle problems of desertification, overgrazing and soil mining.

This workshop on soil fertility management intends to bring together agronomists, livestock experts, soil scientists, economists, sociologists, and extension agents working on soil fertility management and improved land-use systems in the western African context. Researchers and project experts with on-farm experience are especially encouraged to make a contribution to the workshop. Contributions that give experimental data and feasible propositions for better management of soil fertility in in the region will be given priority. The workshop will provide guidelines for future research and recommendations for implementing the urgently needed improvements to traditional land-use systems in Africa. The following topics will be covered.

- *Topic 1: Soil fertility management in the Sudano-Sahelian Zone*
  - technologies for soil conservation, agroforestry
  - possibilities for fertilizer use in low-rainfall areas
  - improved management of crop residues
  - contribution of crop rotation to soil fertility
  - crop/livestock interaction
  - land-use planning/natural resource management
- *Topic 2: Soil fertility management in the humid and subhumid zones*
  - soil fertility management in agroforestry systems
  - stabilization of soil fertility by organic and mineral fertilizer
  - amelioration of fallow systems
  - other technologies for improving soil fertility
  - land-use planning/natural resource management
- *Topic 3: Socioeconomic, institutional, and political aspects of soil fertility management*
  - indigenous knowledge and practices of soil fertility management
  - economic and cultural constraints for the maintenance and amelioration of soil fertility
  - impact of price policy and reduced input subsidies on fertilizer use
  - socioeconomic evaluation of technologies for improved soil fertility
  - participatory approaches in research and development practice
  - institutional building for natural resource management

The Workshop languages will be English and French, for both presentations and posters. Simultaneous translation will be available for all plenary sessions and some of the working group sessions.

Papers/posters on any of the above topics are welcome. Send a one-page abstract in English or French indicating methodology and results to the Workshop Coordinator. Acceptance will be rapidly communicated to authors, who must be prepared to submit their full papers by 15 Dec 1996.

The Programme Committee reserves the right to reject those papers which do not meet the promise of the abstract.

Please indicate any intention to participate to the Workshop Coordinator as soon as you see the notice. For further information please contact:

Tropical Centre for Agriculture (SFB 308)
Andreas Neef (Workshop Coordinator)
University of Hohenheim (793)
D-70593 Stuttgart, Germany
Tel. No + 49 (0) 711-459-2548
Fax No + 49 (0) 711-459-3315
e-mail nigsymp@ uni-hohenheim.de

New ICRISAT Publications

Copies of titles are available on request from:

Distribution Unit
IMEP, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)
Patancheru 502 324, Andhra Pradesh, India

or other sources as indicated,

LDC = less developed country. Highly developed countries (HDCs) include Australia, Canada, European countries, Iran, Iraq, Japan, Kuwait, Libya, New Zealand, Saudi Arabia, South Africa, and USA. All prices include postage.

Leuschner, K., and Manthe, C.S. (eds.) 1996. Drought-tolerant crops for southern Africa: proceedings of the SADC/ICRISAT Regional Sorghum and Pearl Millet Workshop, 25-29 Jul 1994, Gaborone, Botswana. 376 pp. ISBN 92-9066-310-3. Order code CPE 097. Price US$ 23.56 (LDC), US$ 61.16 (HDC), Rs 586.00 (India).

Small-scale farmers in southern Africa have traditionally relied on sorghum and millet to feed their families. Seventy-live delegates from 17 countries participated in the SADC/ICRISAT Regional Sorghum and Pearl Millet Workshop held at Gaborone, Botswana, 25-29 Jul 1994, to discuss ways of improving sustainable food production in semi-arid areas. Recent research on sorghum and pearl millet was reviewed through presentations that discussed the role of three broad disciplines - genetic enhancement, crop protection, and technology transfer - in increasing food security at household level. Priority areas include enhancement of seed production, strategies of crop protection, reliable on-farm trials to identify promising varieties, and more effective technology transfer.

Gowda, C.L.L., and Ramakrishna, A. (eds.) 1996. CLAN Collaborative research in Asia: needs and opportunities. Summary proceedings of the CLAN Country Coordinators' Steering Committee Meeting, 4-6 Dec 1995, ICRISAT Asia Center, India. 128 pp. ISBN 92-9066-346-4. Order code CPE 103. Price US$ 12.34 (LDC), US$ 31.54 (HDC), Rs 304.00 (India).

This publication reports the deliberations of the Steering Committee Meeting of the Cereals and Legumes Asia Network (CLAN). The CLAN Country Coordinators reviewed the activities of the network of 1993-95, and identified the needs and opportunities for future collaborative research and technology exchange. The role of ICRISAT's research project and research support programs was outlined and discussed, as were potential contributions from regional and international institutions.

The recommendations of the meeting include enhanced cooperation and linkages among member countries for research and technology involving sorghum, pearl millet, chickpea, pigeonpea, and groundnut, and related natural resource management in the production systems where these crops are grown.

Baidu-Forson, J., Bantilan, M.C.S., Debrah, S.K., and Rohrbach, D.D. (eds.) 1996. Partners in impact assessment: summary proceedings of an ICRISAT/NARS Workshop on Methods and Joint Impact Targets in Western and Central Africa, 3-5 May 1995, Sadone, Niger, and 9,11-12 May, Samanko, Mali. (Bilingual En, Fr.) 116 pp. ISBN 92-9066-354-5. Order code CPE/F 107. Price US$ 5.50 (LDC), US$ 16.80 (HDC), Rs 165.00 (India).

Regional workshops were held at Sadore, Niger, and Samanko, Mali, to evaluate the joint impact of ICRISAT and National Agricultural Research Systems (NARS) in Western and Central Africa, Twenty-one scientists from ICRISAT and the national programs in Cameroon, Chad, and Niger participated in the workshop at Sadore. The Samanko workshop was attended by 18 scientists from ICRISAT, NARS collaborators in Burkina Faso and Mali, INSAH and the West and Central Africa Sorghum Research Network (WCASRN). National program representatives identified specific jointly developed technologies that should be targeted for impact assessment. Methodological approaches for measuring welfare benefits to consumers and producers were discussed and illustrated with case studies. Minimum dataset requirements were outlined and protocols for case studies on technologies targeted by NARS partners were developed.

Singh, S.D., Wilson, J.P., Navi, S.S., Talukdar, B.S., and Hess, D.E. 1996. Screening techniques and sources of resistance to downy mildew and rust in pearl millet. Information Bulletin no. 48. ISBN 92-9066-352-9. Order code IBE 048. (In press,)

Significant progress has been made in developing highly effective and reliable laboratory/greenhouse and field screening techniques for downy mildew (*Selerospora graminicola*), and in using them to identify resistance, and to develop resistant cultivars. Using these tech-

niques, 4794 accessions of pearl millet, 50 accessions of intermediate weedy forms, and 557 accessions of wild relatives, originating from 40 countries, have been screened in India and/or western Africa, and a large number of resistant sources identified. A total of 26 breeding products have been developed and released for cultivation in India. Similar progress has been made in developing cultivars resistant to rust (*Puccinia* spp).

This bulletin describes all the currently known screening techniques and provides relevant information on important sources of resistance to downy mildew and rust. It is expected to be useful to breeders and pathologists involved in improving pearl millet for genetic resistance to these two diseases.

Food from Thought No. 3. Improving the unimprovable - succeeding with pearl millet. 1996. 14 pp. Order code FTE 003. Single copies free.

'Food from Thought' is a series of narratives on the practical application of research conducted by ICRISAT and its collaborators. The format is a full color brochure. This story describes ICRISAT's remarkable successes in improving pearl millet, particularly in breeding lines with resistance to downy mildew.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1996. ICRISAT Report 1995. 76 pp. ISSN 1017-9933. Order code IRE 005. Price US$ 18.58 (LDC), US$ 48.98 (HDC), Rs 462.20 (India).

Presents a comprehensive sample of the events and achievements of 1995. Contents include an introduction by the Director General and the Chairman of the Governing Board, sections on the year's highlights, financial summaries, technology exchange, plant material releases, and a list of senior staff.

Videos

To spray or not to spray .... 1996. Order code VCE 008. English/VHS-PAL/16 min. Price US$ 10.00 (LDC/HDC), Rs 350.00 (India).

The Green Revolution seemed successful in the sixties and seventies, when the productivity of food crops increased dramatically, largely as a result of the intensive use of inputs, such as fertilizers and pesticides.

However, during the last 20 years, insect pests have become a major problem for many farmers in tropical and subtropical regions. Initially susceptible to insecticides, many of these insects have developed resistance to the chemicals. Farmers spray more often, resistance intensifies, the natural enemies of the pests are killed, and the problem intensifies - this is the *insecticide treadmill.*

Integrated pest management (IPM) procedures help farmers to minimize crop losses without or with limited use of pesticides. Scientists from ICRISAT, together with Indian national program scientists and farmers, have developed IPM procedures for groundnut.

Natural predators of the insect pests, helped by modified cultural techniques, are now the control agents. Using these procedures, farmers can control more than 90% of pest ocxcurrences without insecticides.

Also available in Telugu (***Ladde purugujoru, rythula bejaru***).

Show me, tell me, explain me .... 1996. Order code VCE 007. English/VHS-PAL/16 min. Price US$ 10.00 (LDC/HDC), Rs.350.00 (India).

Presents ICRISAT's participatory work with NGOs and farmers in India's largest pearl millet growing state, Rajasthan. In it, farmers, NGO workers, and scientists discuss techniques for selecting varieties. The video is available in both English and Hindi (***Mujhe samjhaiye***), and was produced by Ulrich Roth, a freelance videographer based in Germany.

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Information for ISMN contributors

Publishing objectives

The International Sorghum and Millets Newsletter (ISMN) is published annually by the Sorghum Improvement Conference of North America (SICNA)and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). It is intended as a worldwide communication link for all those who are interested in the research and development of sorghum (*Sorghum bicolor* (L.) Moench), pearl millet (*Pennisetum glaucum* (L.) R. Br.), and finger millet (*Eleusine coracana* (L.) Gaertn.), and their wild relatives. Though the contributions that appear in ISMN arc reviewed and edited, it is expected that the work reported will be developed further and formally published later in refereed journals. It is assumed that contributions in ISMN will not be cited unless no alternative reference is available.

ISMN welcomes short contributions (not exceeding 600 words) about matters of current interest to its readers.

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Send us the kind of information you would like to see in ISMN.

- **Contributions should be current, scholarly, and their inclusion well-justified on the grounds of new information.**
- Results of recently concluded experiments, newly released varieties, recent additions to germplasm collections, etc.
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- Details of recent publications, with full bibliographic information and 'mini reviews' whenever possible.
- Personal news (new appointments, awards, promotions, change of address, etc.)

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- Keep the items brief—remember, ISMN is a newsletter and not a primary journal. About 600 words is the upper limit (no more than two double-spaced pages).
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ISSN 1023-487X

223-96